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The Role of Cumulus Convection in the Development of Extratropical Cyclones

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ABSTRACT—The goal of this study is to determine whether cumulus convection plays a role in the development of extratropical cyclones, and if it does, to determine the nature of that role. The basic approach is to ascertain whether there is a systematic relationship between the observed extent and degree of convective activity accompanying cyclogenesis and the departure of actual storm evolution from that predicted by large-scale dynamical models.

On the basis of intensive analyses of the two storms initially chosen for study, the following hypothesis was formulated, and the balance of the investigation was directed primarily toward ascertaining its validity:

In some instances of extratropical cyclogenesis, cumulus convection plays a crucial role in the initiation of development through the release of latent heat in the vicinity of the cyclone center. In such cases, dynamical models that do not adequately simulate convective precipitation, especially as it might occur in an environment that is unsaturated, will fail to properly forecast the onset of development.

Further evidence, either to support or refute the hypothesis, was derived from detailed analyses of seven additional storms, cursory examination of 12 others, and both qualitative and quantitative consideration of the physical mechanisms involved. Although not conclusive proof of the hypothesis, the evidence does indeed support it.

Significant convection occurred in the center of storms generally only during the early stages of their life history. Latent heat released by convective showers in the vicinity of the Low center appeared to initiate development before such development would have occurred if only the larger scale baroclinic processes were operative. Convective activity not in the immediate vicinity of the Low center did not appear crucial either to the initiation of development or to the trend of continued development following the onset of cyclogenesis.

1. INTRODUCTION

a. Background and Statement of the Problem

It has been well established that cumulus convection plays a vital role in the development and maintenance of tropical cyclones. From an observational standpoint, Riehl and Malkus (1961) have demonstrated that the important dynamic and thermodynamic processes of a hurricane are highly concentrated in deep cumuli within the storm's core. From a theoretical and numerical modeling point of view, Charney and Eliassen (1964), Kuo (1965), Ooyama (1969), and others have shown that tropical cyclones are forced circulations driven by the release of latent heat in organized convection. In addition, the intense vertical currents of convective cells significantly influence the cyclonic scale circulation through the vertical transports of heat, momentum, and moisture.

Cumulus convection also frequently occurs in association with the development of extratropical cyclones. This is evident from the presence of convective showers as revealed by radar observations, recording rain gage data, and/or surface synoptic reports. In midlatitudes, unlike the Tropics, however, the fundamental mechanism of cyclogenesis is the baroclinic instability of the meandering westerlies (Charney 1947, Eady 1949). Extratropical cyclones thus have as their basic source of energy the large-scale temperature contrast between air masses. Consequently, the importance of cumulus convection with respect to the larger scale baroclinic processes in the evolution of midlatitude storms is not clear, a priori, and has not yet, in fact, been established observationally or theoretically.

One aspect where convection might play a role in extratropical cyclogenesis is in the diabatic process of latent heat release. It has been established that this process per se is often an important contributing factor in overall storm development. Aubert (1957), for example, found that released latent heat tended to lower the heights of isobaric surfaces in the lower troposphere and raise them in the upper troposphere. These changes resulted in deepening of the low-level cyclone and acceleration of the rate of movement. Danard (1964, 1966) demonstrated that the release of latent heat could contribute significantly to the production of a storm's available potential energy and to an increased rate of generation of kinetic energy.

In these and other investigations of this question, little if any consideration is given to the fact that, for whatever difference it might make in either the total amount of condensation or in the temporal and spatial distribution thereof, much of the precipitation accompanying an extratropical storm may be produced by convective updrafts rather than by the more gradual slope ascent characteristic of larger scale baroclinic processes (Tracton 1968).

In addition to the release of latent heat, other, possibly more subtle, influences of convection in extratropical

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storm development might be the vertical transports of such quantities as heat, momentum, and moisture. These processes are significant in tropical cyclogenesis, and there is no reason to believe that they may not be of some importance in the development of extratropical cyclones.

The goal of this study is to determine whether cumulus convection plays a role in the evolution of extratropical cyclones, and, if it does, to determine the nature of that role. It is felt that this question warrants consideration because of its importance to a complete understanding of the complex phenomenon of cyclogenesis and its implications to numerical weather forecasting.

b. Basic Approach

A direct and comprehensive analysis, either descriptive or dynamic, of the interactive role of cumulus convection and large-scale baroclinic development would be exceedingly difficult, if at all physically or economically feasible. Observationally, a very dense network of stations would be required to describe the interactions of convective and larger scale motions and processes. Existing mesoscale networks, such as that operated by the National Severe Storms Laboratory in Oklahoma, cover areas that are small compared to the domain of a cyclone, and, furthermore, these areas are fixed geographically. From a theoretical standpoint, the problem is analytically intractable. Numerical integration of the governing equations wherein the cumulative effects of convection on the synoptic scale development are parameterized is possible; however, the computational and physical complexities of a dynamic model designed explicitly for investigation of the role of cumulus convection in extratropical cyclogenesis would be numerous. Moreover, it is often as difficult in a numerical model as in the real atmosphere for one to keep track of all possible interactions and their consequences.

Thus, an indirect approach was adopted for this investigation wherein it was sought to determine whether there is a relationship between the extent of convective activity within extratropical cyclones, as ascertained from conventional meteorological data, and the departure of actual storm evolution from that predicted by operational forecast models. Insofar as these models do not incorporate or adequately formulate the effects of sub-grid-scale convection, the emergence of a consistent relationship in the analysis of several storms would indicate that cumulus convection systematically alters the course of synoptic scale development from that which would be expected if larger scale processes alone were operative. The nature of such a relationship would, of course, reflect the nature of the role of convection in extratropical cyclogenesis and guide consideration of the physical mechanisms involved.

c. Formulation of the Hypothesis

At the outset of this study, the role of convection in the evolution of extratropical cyclones was not assumed, nor was it explicitly assumed that convection indeed played a role. Initially, two storms were chosen for analysis; the intense cyclogenesis along the east coast of the United States on Nov. 11–13, 1968, and the less dramatic but nevertheless major development over the central United States on Mar. 22–23, 1969. The observed degree and extent of convective activity associated with each storm was ascertained to the fullest extent permitted by the data and methods of analysis outlined in subsection 2b. An extensive analysis was then made of the difference between the forecast and actual evolution of the storms.

In both cases, the numerical prognoses (the National Meteorological Center's primitive-equation model, NMC–PE) did forecast cyclogenesis in terms of deepening of the central pressure and itensification of the cyclonic circulation of the sea-level system. The forecasts, however, were not without errors; the most notable with respect to possible implications of the role of convection was the failure in the November case to properly forecast the initiation of development. More specifically, the model lagged behind the real atmosphere in forecasting the onset of development. The observed initiation of cyclogenesis was accompanied by intense convective showers in the unsaturated environment of the cyclone center. Since the large-scale processes that the model purports to represent require saturation to produce precipitation, the forecasts failed to predict the release of latent heat associated with the convection.

The initial development of the March storm was also accompanied by convective showers in the vicinity of the Low center. In this case, however, the environment was sufficiently near saturation so that the rainfall and concomitant latent heat release were predicted, and the onset of development was properly forecast. The analyses of these two cases, therefore, suggested that the release of latent heat by cumulus convection may be, at least in some instances, a critical factor in the initiation of cyclogenesis.

In both cases, there were many errors in the detail and magnitude of the forecast patterns, other than the lag phenomenon in the November storm. These errors, however, did not appear to be related to differences or similarities in the extent and degree of the convective activity associated with the storms. Moreover, detailed analyses of the cases suggest that systematic errors in the numerical prognoses of cyclogenesis other than the lag phenomenon, if they indeed exist, would probably be obscured by the noise of other physical or computational limitations of the model, or a prohibitively large number of storms would have to be analyzed for their existence to become apparent. Prohibitive here is defined in terms of the difficulty and cost of acquiring data and the time necessary for analysis of each case.

At this point in the study, therefore, the following hypothesis was formulated, and the balance of the investigation directed primarily toward ascertaining its validity.

> In some instances of extratropical cyclogenesis, cumulus convection plays a crucial role in the initiation of development through the release of latent heat in the vicinity of the cyclone center. In such cases, dynamical models that do not adequately simulate convective precipitation, especially as it might occur in an environment that is unsaturated, will fail to properly forecast the onset of development.

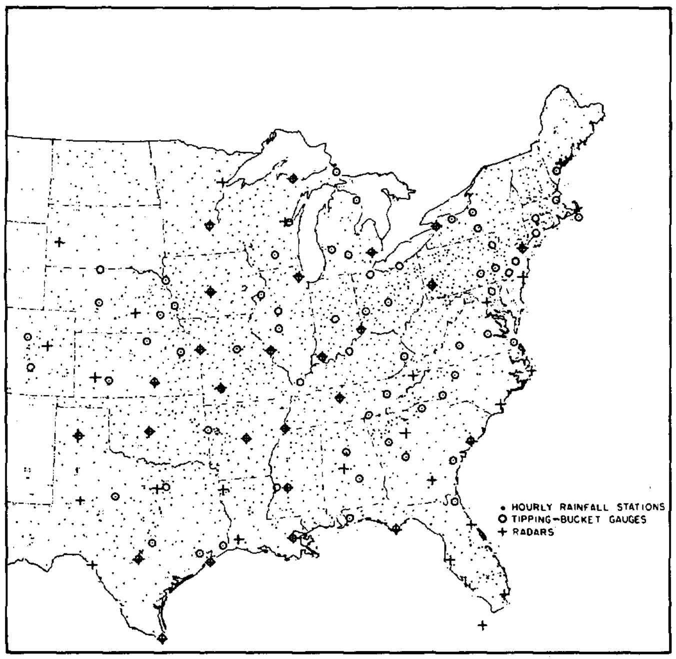


FIGURE 1.—Location of hourly rainfall stations, tipping-bucket gages, and weather radar. (The general operating range of radar is 250 n.mi. The effective range for detecting precipitation, however, is somewhat less because of earth curvature effects and beam spreading.)

TABLE 1.—*Dates of the nine detailed case studies*

Case	Dates
1	Feb. 4–5, 1971
2	Apr. 1–3, 1970
3	Nov. 11–13, 1968
4	Mar. 2–4, 1971
5	Feb. 12–13, 1971
6	Mar. 23–24, 1969
7	Feb. 26–27, 1971
8	Dec. 25–27, 1970
9	Jan. 25–26, 1971

Seven additional storms were analyzed in detail with respect to their bearing on the hypothesis, and cursory examination was made of 12 others. Also, to complement these basically empirical considerations, both the qualitative and quantitative aspects of the physical mechanisms involved were examined.

2. METHODS OF ANALYSIS

a. Choice of Cases

Nine storms were analyzed in detail for this investigation. The dates of each are listed in table 1. In no instance was a storm chosen for analysis because of any prior specific knowledge of the performance of the numerical prognoses or the degree of convection associated with the observed cyclogenesis. Criteria for selection were the intensity of actual development, availability of numerical forecasts, and sufficient data to determine the extent of convective activity from the structure of precipitation patterns.

A storm for which there was a 12-hr period having an average surface deepening rate of at least 1 mb/hr was considered an intense development. Except for that of Dec. 25–27, 1970, cases were restricted to storms that developed over the relatively data-rich eastern two-thirds of the United States or to storms that remained close enough to the Atlantic coast so that a major portion of the precipitation either fell over land or was within the range of land-based radar. Primary interest in the Dec. 25–27, 1970 case, a storm with major development well out over the Atlantic,[2] was a comparison of the NMC-PE forecasts with those available from test runs of the limited-area, fine-mesh version of this model (LFM). Emphasis on storms of the 1970–71 winter season reflects the September 1970 operational implementation of the Fleet Numerical Weather Central's primitive equation model (FNWC-PE). (A brief description of the general aspects of the models appears in subsection 2c.)

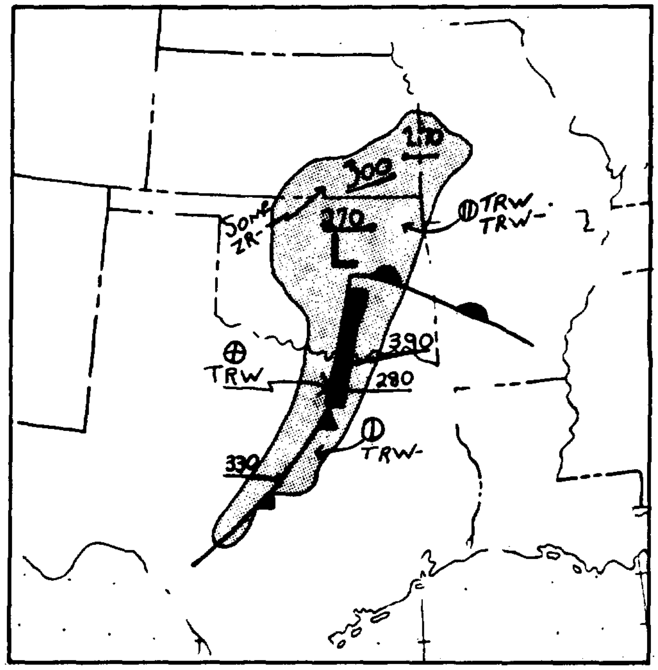


FIGURE 2.—Composite of the radar summary chart and simplified surface analysis for 1200 GMT, Feb. 4, 1971. Stippling indicates areal echo coverage. Shading indicates area of squall line. For the meaning of symbols, see table 1.

b. Methods Utilized in the Analysis of Convective Activity

Significant convection is assumed to occur only in regions of convective precipitation. The extent and degree of convective shower activity accompanying development of a storm was deduced from composite analyses of weather radar data, tipping-bucket rain gage traces, hourly rainfall amounts, and surface synoptic reports. The weather radar observations are those of the National Oceanic and Atmospheric Administration's network of WSR–57s. Radar locations over the eastern two-thirds of the United States are shown in figure 1. Radar data, in the form of summary charts of the nationwide distribution of precipitation echoes, enable one to depict the broad features of the distribution and character of the precipitation pattern about the storm in question. Figure 2, for example, is a

[2] The initial stages and development, however, were along the coast.

TABLE 2.—*Symbols used in radar charts*

Symbol*	Character of Echoes: Echo System	Definition
⌽	Widely scattered area	Related or similar echoes covering 1/10 of the reported area.
⦷	Broken area	Related or similar echoes in a pattern that covers 6/10 or more of the reported area but contains breaks or corridors.
⊕	Solid area	Contiguous echoes covering, usually more than 9/10 of the reported area.
▭	Line of echoes (scattered, broken, or solid)	Related echoes in an extended pattern.

Note: ●——— (HHH) indicates position of individual cells imbedded in echo system. HHH is height of echo top in hundreds of feet.

Characteristic Type of Precipitation: Symbol	Precipitation
R	Rain
S	Snow
RW, SW	Showers
TRW	Thundershowers
Z	Freezing precipitation

Echo Intensity: Symbol	Estimated Precipitation Rate (in/hr)
− −	Very light (<0.01)
—	Light (0.01–0.1)
	Moderate (0.1–1.0)
+	Heavy (1.0–5.0)
++	Very heavy (>5.0)

*Symbols and meanings as described in *Weather Radar Manual (WBAN), Part A*, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Washington, D.C.

composite of the radar chart and the simplified surface analysis for 1200 GMT on Feb. 4, 1971. The meanings of the symbols used on the radar charts appear in table 2.

An important feature of the radar data is the reported heights of the tops of cells. In figure 2, the maximum top reported is that of a 39,000-ft-high cell located in the squall line. Generally speaking, the greater the height of the cells, the more intense is the convection.

A more refined and quantitative picture of the extent and degree of convective activity than that obtained by radar was ascertained from surface measurements of rainfall. The two types of data used are: hourly precipitation amounts and tipping-bucket records of the continuous temporal variation of rainfall rate. Of these, the tipping-bucket data are more definitive in delineating the presence and intensity of convective showers; however, as can be seen from figure 1, the density of stations reporting hourly totals is much greater than that for tipping-bucket gages.

The tipping-bucket gages record precipitation with a time resolution of about 1/4 min. As can be seen by comparing figures 3A or 3B with figure 3C, this is sufficient to differentiate between steady stratiform rain and rainfall fluctuating rapidly in space and time as is characteristic of convective showers. The duration of individual showers over a gage depends upon their speed of movement and horizontal dimensions and is on the order of several minutes. Peak precipitation rates, which may be considered a measure of the intensity of convection, usually are greater than 0.3 in/hr and may often exceed 2 in/hr.

Since the tipping-bucket gages are geographically fixed, they in effect record the instantaneous precipitation rate along line segments that connect successive positions of the station with respect to moving features of the surface system. For example, figure 3A is the rain gage trace of Charleston, S.C., for the period 1900–2300 GMT on Nov. 11, 1968. The line segment with respect to the Low center and fronts along which the precipitation cross section applies is shown schematically. Figure 3A shows that between 2100 and 2230 GMT Charleston experienced a series of heavy showers, which placed this convective activity just to the north-northwest of the Low. In comparison, the rain gage record at Pensacola, Fla., between 0900 and 1200 GMT on Nov. 11, 1968 (fig. 3B) indicates the presence of convective showers, but the activity is much more subdued than that exemplified by the Charleston trace. From figure 3C, one can see that, at the same time the Pensacola trace indicates shower activity in the vicinity of the Low center, the record for Montgomery, Ala., shows steady, exclusively nonconvective rainfall some 150 mi to the north.

The same approach used in consideration of the tipping-bucket records can be applied to stations that report only the cumulative 1-hr precipitation amounts. Although the intensity of individual showers cannot be determined, the magnitude of the convection can be assessed in terms of the hourly totals.[3] Figure 4, for example, presents a histogram of the successive 1-hr rainfall amounts recorded during a series of thunderstorms at (A) Tulsa and (B) Lehigh, Okla., between 1000 and 1500 GMT on Feb. 4, 1971. (See also radar chart, fig. 2.)

From the preceding discussion, it should be clear that, through judicious analysis of radar and rain gage data, a fairly detailed picture of the extent and degree of convective activity accompanying development of a particular storm can be obtained. In the actual analyses, a description was compiled of the distribution and magnitude of convection on essentially a continuous basis as the storm evolved; that is, time resolution of 1–3 hr. It should be emphasized here that no attempt was made to keep track of individual convective cells. Instead, concern was with the macroscale distribution and magnitude of convection with respect to the developing cyclone. The goal of this study is to determine whether the convection so described plays a role in the overall storm development.

c. General Aspects of the Models

Three dynamical forecast models were used in this investigation: (1) the six-layer, primitive-equation model of the National Meteorological Center (NMC-PE), (2) the limited-area, fine-mesh version of the NMC-PE (LFM), and (3) the five-layer, primitive-equation model

[3] There is, of course, some uncertainty in assessing the hourly precipitation data because of the inherent time smoothing involved. It is possible, for example, that the sum of the reported totals for two successive hours actually all fell in a time span of 1 hr (or less). Such possibilities were considered in the storm analyses.

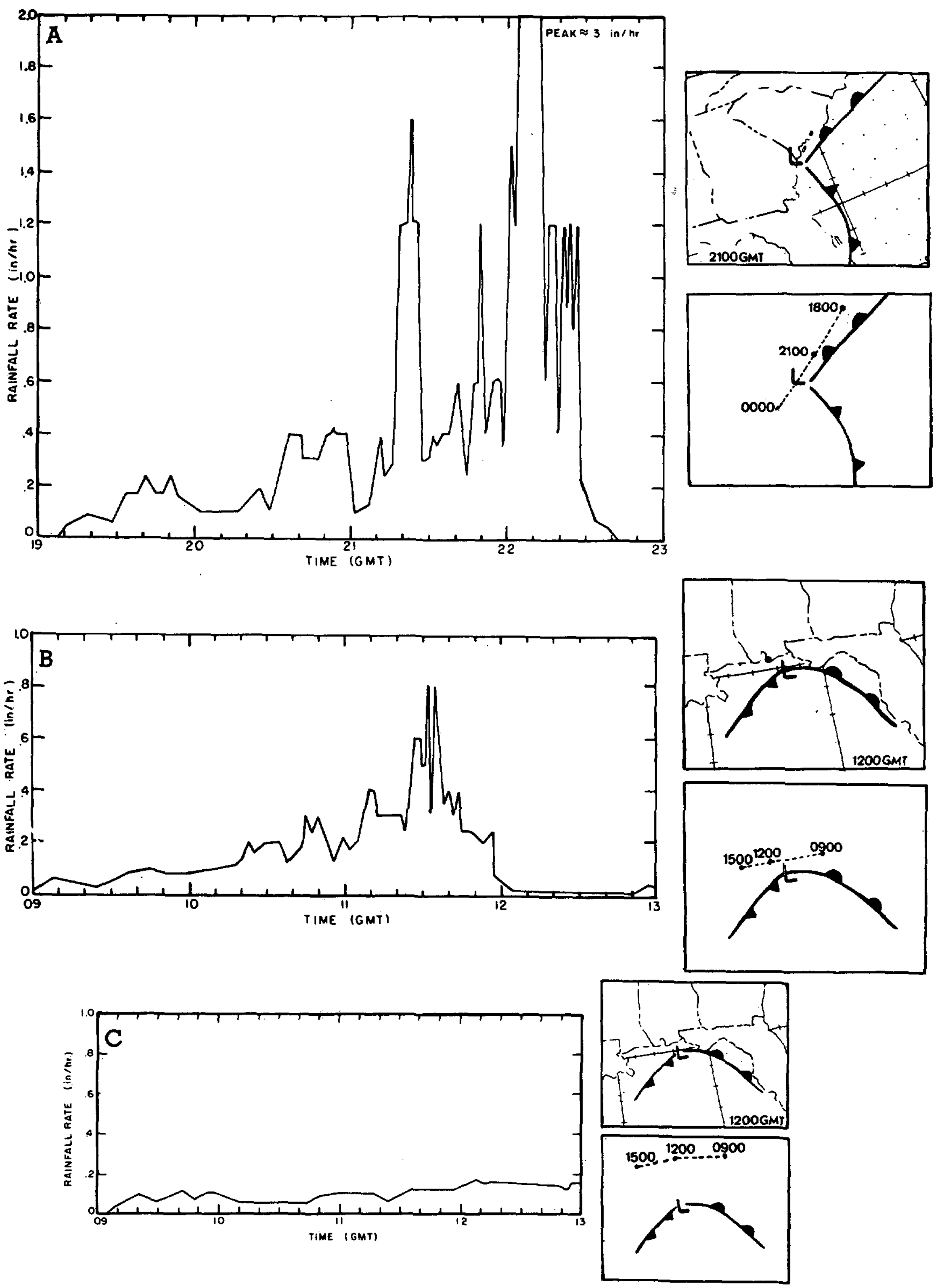


Figure 3.—Nov. 11, 1968, tipping-bucket recording rain gage traces with schematic showing line segments along which precipitation cross sections apply for (A) Charleston, S.C., (B) Pensacola, Fla., and (C) Montgomery, Ala. Top figure of schematics indicates geographical location of station at specified time; bottom figure shows successive positions of station with respect to the moving surface system.

of the Fleet Numerical Weather Central (FNWC-PE). The basic features of the NMC-PE have been described by Shuman and Hovermale (1968); Howcroft (1971) has discussed the LFM. The principal aspects of the FNWC-PE have been described by Kesel and Winninghoff (1972).

The NMC-PE became operational in June 1966, and the FNWC-PE was implemented in September 1970. Forecasts are generated twice daily from the nominal times of 0000 and 1200 GMT. The LFM forecasts used were test runs of this model made prior to its operational implementation in October 1971. Table 3 summarizes, for each of the initial times relevant to the nine storms analyzed in detail, the models for which forecasts were available.

Consideration of the forecasts of more than one model, when possible, was motivated by a desire to check and

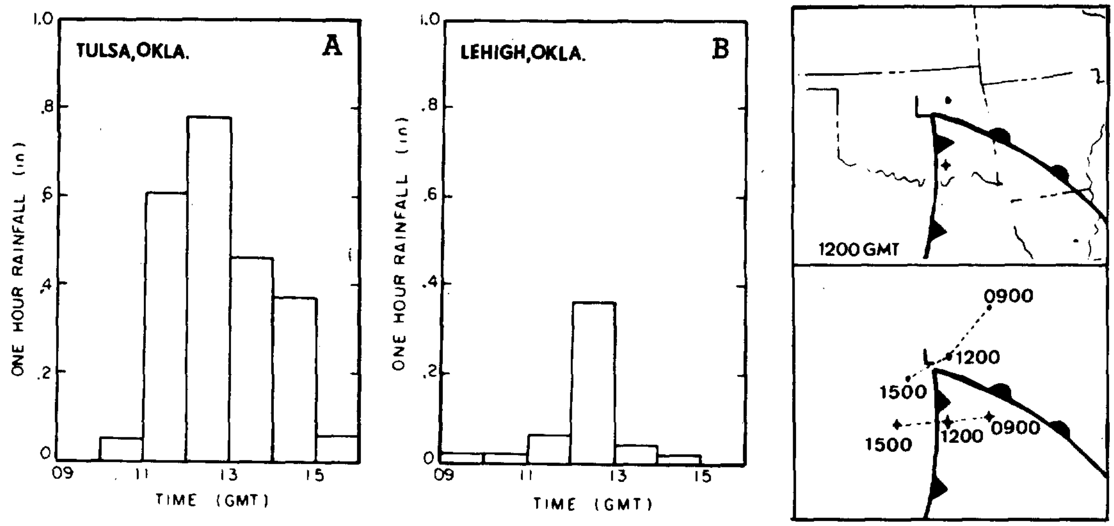


FIGURE 4.—Feb. 4, 1971, rainfall histograms with schematic showing line segments along which cross sections apply for (A) Tulsa, Okla. (dot on schematic) and (B) Lehigh, Okla. (plus on schematic). Top figure of schematic indicates geographical location of stations at 1200 GMT, the bottom figure shows successive positions of stations with respect to the moving surface system.

augment any deductions gleaned from one model's prognoses alone. The equation systems and basic physics of the LFM are the same as those of the NMC-PE; the principal differences are the areal coverage and the horizontal grid spacing. Thus, any inconsistency in the deductions drawn from the forecasts of these two models would likely reflect either the lesser truncation error in the LFM or the more refined specification of initial conditions. Differences between the NMC-PE and FNWC-PE forecasts could reflect any one of a number of physical and computational dissimilarities. Particular interest, however, was on any difference in the forecasts that might reflect a difference in the method of parameterizing small-scale convection. The NMC-PE (and LFM) utilizes the so-called "convective adjustment" scheme wherein the lapse rate is adjusted to the moist adiabatic when it is forecast to exceed that value *and* at the same time the grid column is forecast to be saturated. In effect, the lapse rate is neutralized through an upward transport of heat. There is no specific allowance, however, for the convective rainfall and concomitant release of latent heat that can occur in an unsaturated environment.[4] In essence, the convective adjustment in the NMC-PE (and LFM) is more a mechanism for preventing the computational instability that would result without such adjustment than a meaningful attempt to incorporate convection.

The FNWC-PE, on the other hand, more explicitly considers convection through use of a parameterization scheme adapted from that used in the Mintz-Arakawa general circulation model. In this scheme, energy parameters are used in conjunction with measures of the total upward convective mass flux, as well as entrainment, to determine a specific convective component of precipitation and the vertical redistribution of heat and moisture.

TABLE 3.—*Forecasts available for the initial times relevant to the nine detailed case studies*

Case	Initial Time (GMT)	NMC-PE	FNWC-PE	LFM
1	1200 Feb. 4, 1971	X	X	
	0000 Feb. 5, 1971	X	X	
2	1200 Apr. 1, 1970	X		
	0000 Apr. 2, 1970	X		
3	0000 Nov. 11, 1968	X		
	1200 Nov. 11, 1968	X		
	0000 Nov. 12, 1968	X		
4	1200 Mar. 2, 1971	X	X	
	0000 Mar. 3, 1971	X	X	
	1200 Mar. 3, 1971	X	X	
	0000 Mar. 4, 1971	X	X	
5	0000 Feb. 12, 1971	X		
	1200 Feb. 12, 1971	X	X	X
	0000 Feb. 13, 1971	X	X	
6	0000 Mar. 23, 1969	X		
	1200 Mar. 23, 1969	X		
7	0000 Feb. 26, 1971	X	X	
	1200 Feb. 26, 1971	X	X	
8	1200 Dec. 25, 1970	X	X	X
	0000 Dec. 26, 1970	X	X	
9	1200 Jan. 25, 1971	X	X	
	0000 Jan. 26, 1971	X	X	

This parameterization scheme does give the FNWC-PE the capability to simulate convective precipitation that can occur in an unsaturated environment; however, the lack of sufficient vertical resolution in the model limits its ability to represent the frequent pre-convective outbreak condition of a mixed moist layer topped by an inversion with potentially unstable air above.

d. General Procedure Used in Storm Analysis

For each storm, the actual course of the synoptic scale development was traced via NMC sea-level pressure analyses at 3-hr intervals. In most instances, the central

[4] The NMC-PE and LFM can predict precipitation prior to the time when grid-scale saturation is forecast, since saturation in the models is defined in terms of a threshold value of relative humidity of between 70 and 100 percent. The motivation for using a reduced saturation criterion is primarily to account for the stable (stratiform) precipitation that can occur before grid-scale saturation, rather than to make any meaningful attempt to simulate convective precipitation in an unsaturated environment.

pressure served as an adequate indicator of the degree of cyclogenesis; however, note was made of situations where development was manifested more by an increase in the intensity of the cyclonic circulation, assessed qualitatively, than by a decrease of central pressure.

The extent and degree of convective activity accompanying the observed development were deduced from precipitation patterns in the manner described in subsection 2b. The forecast and actual evolutions of the storm were then compared. In evaluation of the performance of forecasts, emphasis was on the departure between predicted and actual changes rather than on the absolute difference between observed and forecast at some given time. This is especially pertinent with regard to the hypothesis where, for example, the absolute error in a 36-hr forecast of central pressure is less important than comparison of the temporal evolution of the actual and predicted development.

It should be noted that the numerical prognoses are through 24 or 36 hr from the initial time (either 0000 or 1200 GMT) with generally two or more successive initial times considered for each case. Since the output of the numerical forecasts from some given initial time is in 12-hr increments, comparison is with the net 12-hr observed changes between the nominal times of 0000 and 1200 GMT. Another point to note is that the initial 12-hr forecast changes of central pressure are reckoned from the minima of pressure of the objectively analyzed fields of sea-level pressure from which the prognoses are generated. Because of the inherent smoothing that occurs in the objective analyses of data to a coarse grid, the initialized values of central pressure were generally greater (1–5 mb) than the lowest pressures indicated on the corresponding manually analyzed surface charts that were used to trace the actual storm development.

In addition to development of the sea-level pressure system, other potentially relevant items such as precipitation and 500-mb forecasts were examined.

3. DISCUSSION OF THE CASE IN SUPPORT OF THE HYPOTHESIS

a. Introduction

The hypothesis presented in subsection 1c was formulated as a statement of provisional conjecture based upon intensive analyses of two case studies. Further evidence either to support or refute the hypothesis was derived from detailed analyses of seven additional storms, cursory examination of 12 others, and both qualitative and quantitative consideration of the physical mechanisms involved. The purpose of the following discussion is to summarize the evidence and show that, although it may not be conclusive proof of the hypothesis, it does provide sufficient support to elevate its stature from mere conjecture to an assertion that may be accepted as highly probable.

The case in support of the hypothesis may be summarized in terms of the following four arguments:

1. In some storms, there was a coincidence in time between the *initial development* and the occurrence of convective showers in the vicinity of the Low center. Almost invariably, the environment in which the convection occurred was unsaturated.[5]

2. In those cases in which the initial development was accompanied by convective showers in the vicinity of the Low center and the environment in which the convection occurred was unsaturated, the dynamic prognoses systematically failed to properly forecast the onset of development, apparently because of the models' failure to predict the convective rainfall.

3. The importance of the latent heat release by cumulus convection to the initiation of development of some extratropical cyclones, which is implied by the apparent source of the systematic error, is physically plausible and quantitatively reasonable.

4. There appears to be no defensible alternative explanation for the observed systematic error.

TABLE 4.—*Characterization of the initial development of the nine detailed case studies*

Case	Convective precipitation in storm center?	Environment of Low saturated?	Convective precipitation predicted?	Adequate forecast of the onset of development?
1	Y*	N	N	N
2	Y	N	N	N
3	Y	N	N	N
4	Y	N	N	N
5	Y	N	N	N
6	Y	Y	Y	Y
7	N	N	—	Y
8	N	N	—	Y
9	N	N	—	Y

*Y=yes, N=no.

b. Arguments 1 and 2: Coincidence in Time Between Convection and Initial Development; Systematic Error in the Numerical Prognoses

To facilitate the discussion of arguments 1 and 2, table 4 presents for each of the nine storms analyzed in detail a dichotomous characterization of the initial development with respect to the following: (1) the occurrence or nonoccurrence of convective showers in the vicinity of the Low center, (2) saturation or nonsaturation of the environment of the center of the storm, (3) prediction or nonprediction of the convective rainfall, if it occurred, and (4) adequate or inadequate forecast of the onset of development. In those cases where the forecasts of more than one model were available, the conclusions to be drawn from each were consistent with one another. Discussion of the results of cursory examination of 12 additional storms is presented at the end of this subsection.

With regard to argument 1, table 4 shows that the initiation of development of six of the nine storms was accompanied by convective shower activity in the vicinity of the Low center. In only one of these cases was the environment of the Low saturated. It follows, of course, that the initial development of three of the nine storms was not accompanied by shower activity. Furthermore, since the environment about the center of these storms was also unsaturated, there was little or no stratiform

[5] A saturated region is defined here as one in which the mean surface–500-mb relative humidity, as on the operational charts received over facsimile, is in excess of 90 percent. The concept of saturation and nonsaturation is in and of itself unimportant. What is important is the fact that, while saturation is a necessary condition for significant stratiform precipitation, heavy convective rainfall may occur in an environment that is unsaturated.

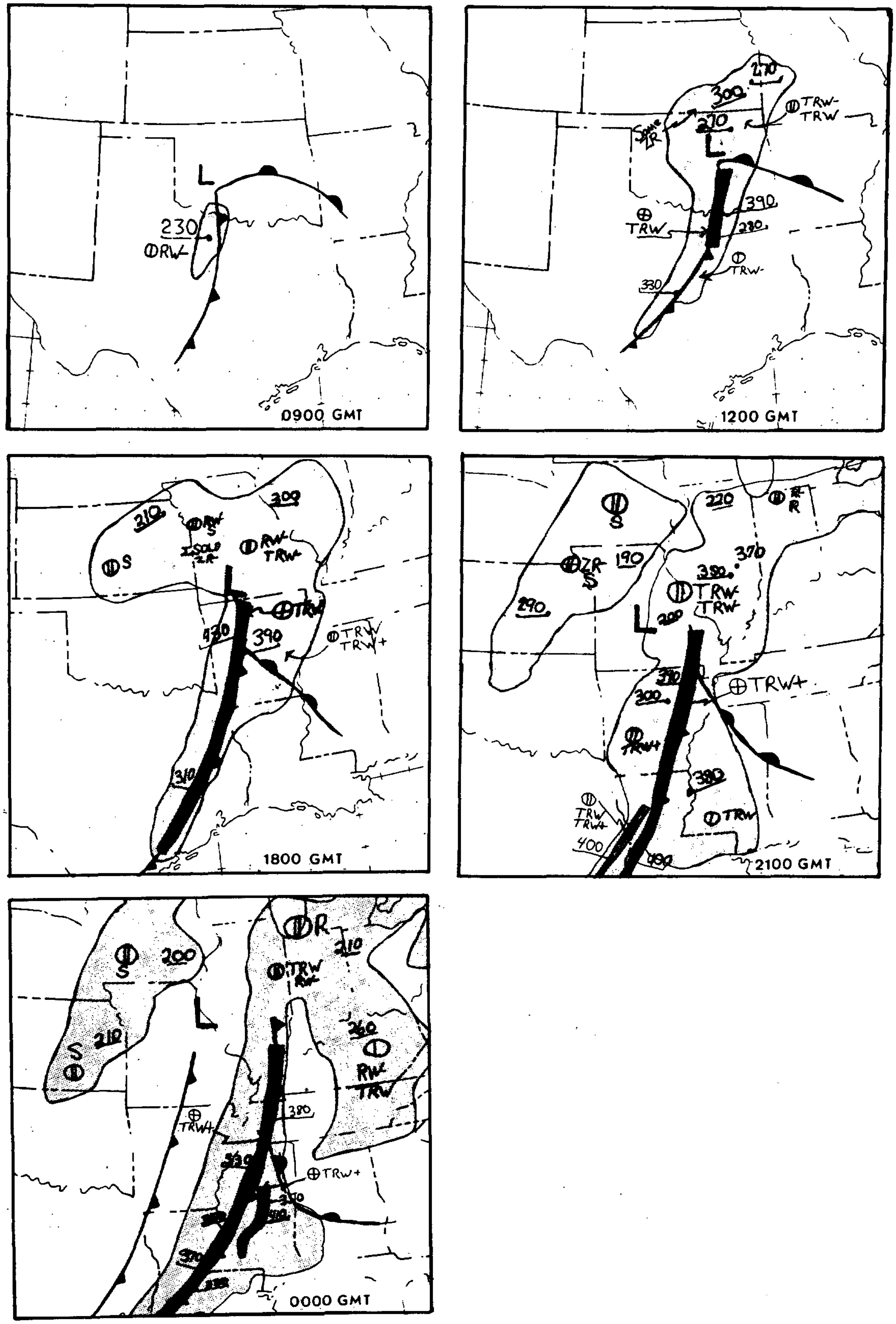


FIGURE 5.—Same as figure 2 for times indicated.

precipitation and, hence, latent heat release was not a factor in the initiation of their development.

With reference to argument 2, table 4 indicates that in each of the five cases where the initial development was accompanied by showers in an unsaturated environment, the dynamical prognoses failed both to predict the convective precipitation and to adequately forecast the onset of development. In the one storm in which convection occurred in an environment that was saturated, the precipitation was predicted, as was the initiation of development. Also, the onset of development was properly forecast in those cases where there was no convection. Hence, the dynamical prognoses systematically failed to predict the onset of cyclogenesis in those storms in which the initial development occurred in association with convective shower activity in an unsaturated environment. Furthermore, the apparent source of the systematic error was the failure of the models to simulate the rainfall produced by cumulus convection in an environment that was unsaturated.

It is noted that significant shower activity occurred in the center of the storms generally only during the early stages of their life history. Following an initial period of development, which lasted anywhere from 6 to 36 hr, the convection became dissociated from the Low center. Forecasts that were generated subsequent to the actual onset of cyclogenesis but prior to the dissociation process were consistent with the notion of the importance of convection in the Low center to the initial development in that when the precipitation was predicted, so too was the trend of continued development.

An additional significant point relevant to arguments 1 and 2 is that convective activity appeared to be important to the onset or continued development of the storms only when it occurred in the immediate vicinity of the Low center. That is, only when the convection occurred in the Low center was there a consistent contemporary relationship between it and the observed storm evolution or was there a systematic error in the numerical prognoses.

Cases 1, 6, and 7 are discussed in this subsection to further scrutinize and document arguments 1 and 2. The other detailed case studies are discussed in Tracton (1972).

Case 1: February 4–5, 1971. During the 18-hr period prior to 1200 GMT on February 4, a low-pressure system moved from New Mexico to central Oklahoma without developing. There was no significant convective activity associated with this system through 0900 GMT on February 4. The 0900 GMT composite surface radar chart (fig. 5) shows the presence of a small area of light showers to the south of the Low along the cold front, but, to this point, hourly rainfall data indicated that negligible amounts of precipitation were produced. Between 0900 and 1200 GMT, as shown by the radar observations (fig. 5), however, and more precisely between 1100 and 1200 GMT, as was indicated by hourly precipitation data, the extent and degree of shower activity increased explosively. Shortly after 1200 GMT, the Low began to deepen (fig. 6).

During the initial period of development between 1200 and 1800 GMT on February 4, radar observations show a line of thundershowers (i.e., a squall line) extending south of the Low embedded in a more general area of scattered to broken showers and thunderstorms which extended and broadened somewhat to the north of the Low. Composite charts of the mean surface–500-mb relative humidity and simplified surface analysis (fig. 7) show that the convection occurred in an unsaturated environment. An indication of the magnitude of the shower activity can be ascertained from the rainfall histograms of Tulsa and Lehigh (fig. 4). The Tulsa histogram, which represents a cross section through the Low center between 1100 and 1500 GMT, indicates a peak 1-hr rainfall amount of 0.80 in. In contrast, the largest 1-hr total deposited as the squall line passed over Lehigh was 0.36 in. The 1-hr

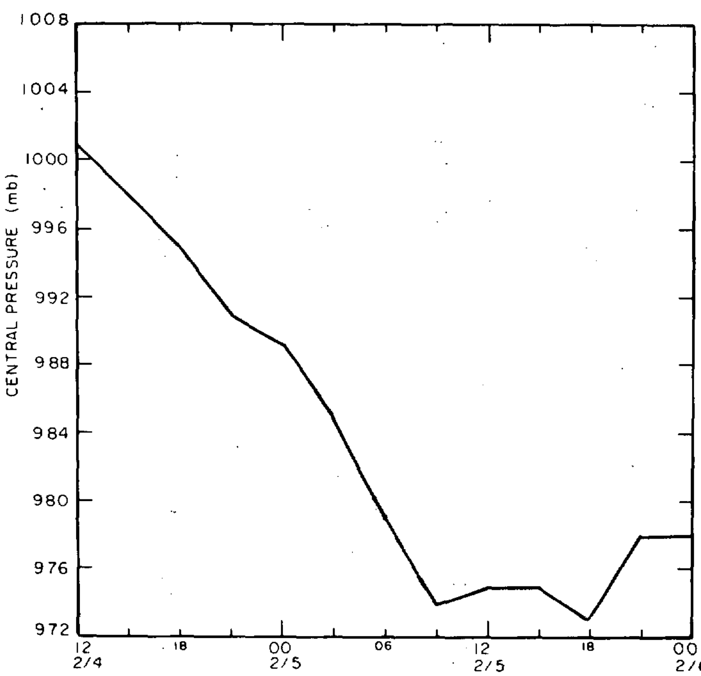


FIGURE 6.—Observed central pressure vs. time (central pressure plotted generally at 3-hr intervals) for case 1.

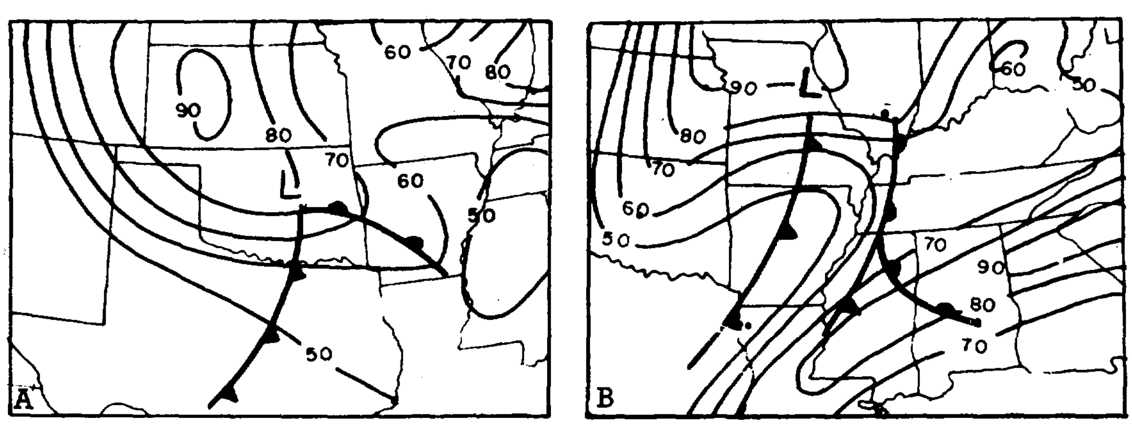
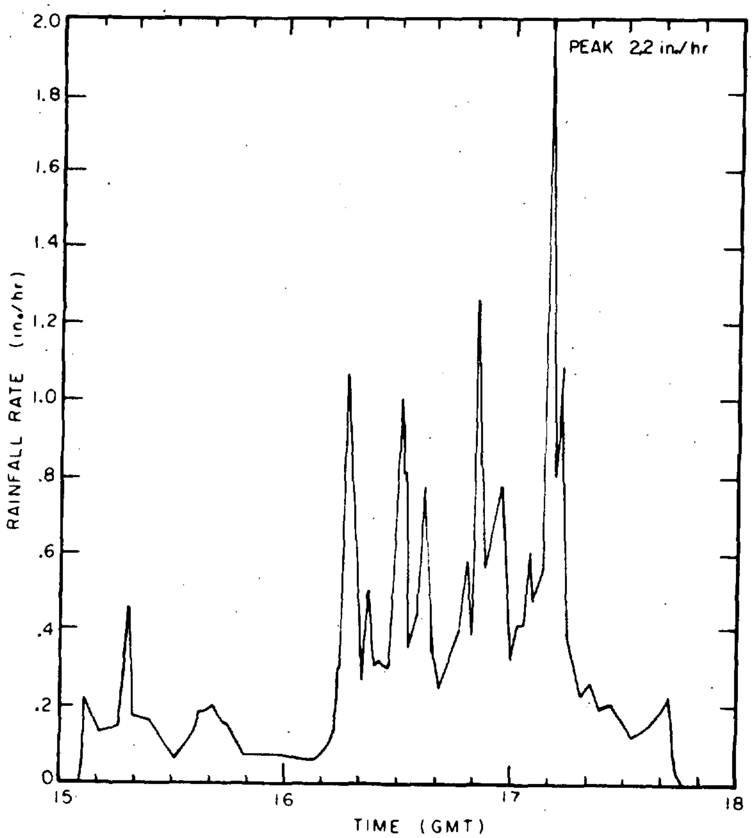


FIGURE 7.—Composite charts of the mean surface-to 500-mb relative humidity (percent) and simplified surface analysis for (A) 1200 GMT, Feb. 4, 1971, and (B) 0000 GMT, Feb. 5, 1971.



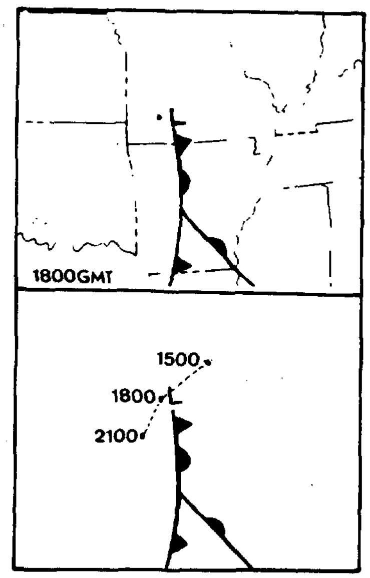


FIGURE 8.—Same as figure 3 for Springfield, Mo., on Feb. 4, 1971.

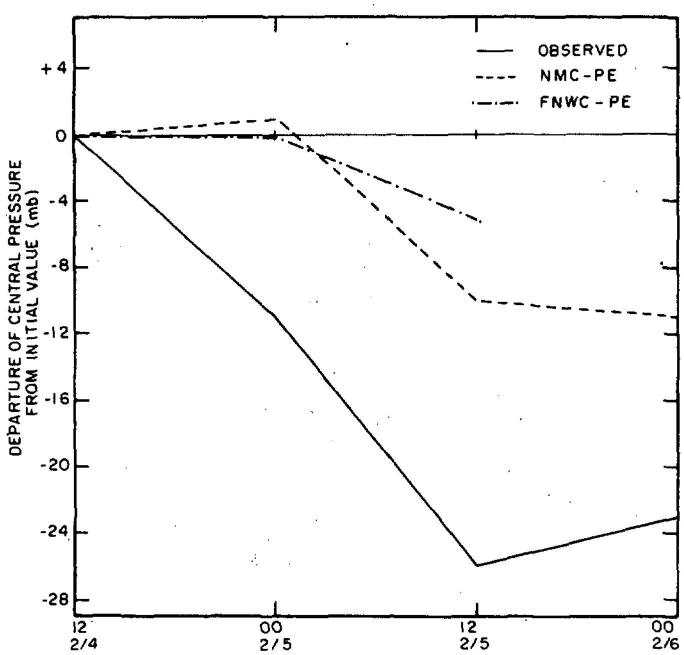


FIGURE 9.—Observed and forecast central pressure vs. time in terms of departure from initial value at 1200 GMT, Feb. 4, 1971. (Values are plotted at 12-hr intervals; 36-hr FNWC-PE is not available.)

amounts north of the storm were similarly less. Thus, although the intensity of individual showers, as implied by the radar echo tops, was greatest in the squall line, the degree of convection, in terms of the net amounts of rainfall produced, was greatest in the center of the storm. The only available tipping-bucket gage relevant to the immediate discussion was that of Springfield, Mo. (fig. 8), which indicates that the intensities of showers in the center of the Low between 1500 and 1800 GMT were generally from 0.50 to 1.0 in./hr, with one peak in excess of 2.0 in./hr. Subsequent to 1800 GMT on February 4, the storm continued to intensify as it moved northeastward toward the Great Lakes. As can be seen clearly from the series of surface radar charts (fig. 5), however, the convective activity began to spread eastward away from the center of the storm between 1800 and 2100 GMT. By 0000 GMT on February 5, there was virtually no precipitation in the vicinity of the Low center.

At this point, it is desirable to note that the configuration of the shower activity during the initial phase of development of this storm is characteristic of each storm in which the onset of development was accompanied by an outbreak of convection. More specifically, reference is made, first, to the 1200 GMT radar chart and, second, to the maximum in the convectively produced amounts of rainfall within the center of the storm.

One can see from figure 9 that neither the NMC-PE nor the FNWC-PE prognosis generated from 1200 GMT data on February 4 properly forecast the initiation of development. The models did forecast cyclogenesis in the sense that significant deepening was predicted between 12 and 24 hr after the initial time, but each lagged behind the real atmosphere in the onset of development. Figure 10 shows that during the 12-hr period immediately following 1200 GMT on February 4, when the observed initial development occurred, both models produced negligible

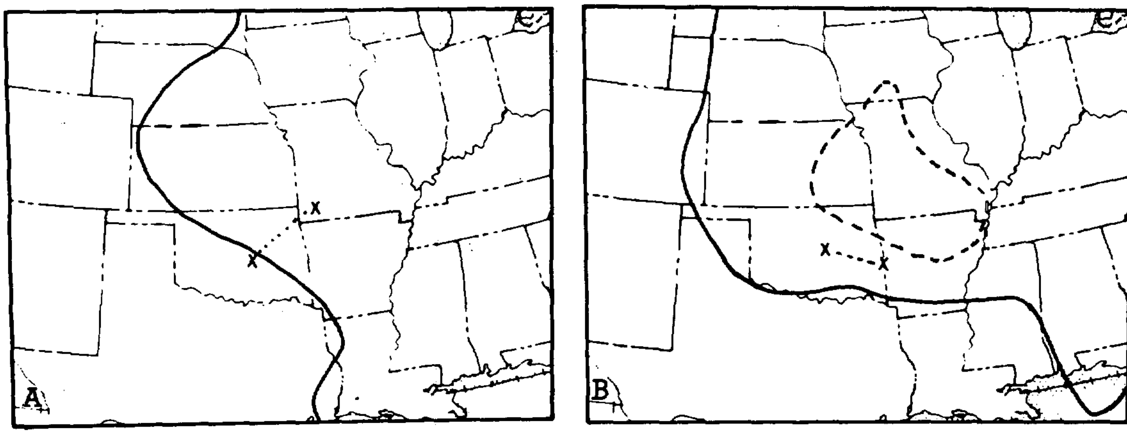


FIGURE 10.—Twelve-hour precipitation forecasts from 1200 GMT, Feb. 4, 1971 data for (A) FNWC-PE and (B) NMC-PE. Solid line contours: 0.01, 0.50, 1.0 in. etc; dashed line intermediate contours at 0.25-in. intervals. Track of the forecast Low center (X------X) is superimposed.

amounts of precipitation (<0.25 in.) about the forecast center of the low pressure.[6]

Note that both the (A) NMC-PE and (B) FNWC-PE prognoses generated from 0000 GMT on February 5, which was after the shower activity became dissociated from the Low center, properly forecast the continuation of development in the 12-hr period immediately following the initial time (fig. 11). The degree of the forecast development, which was about the same in both cases, was less than observed, but there was no lag in the trend of continued development. What is important in this regard is that while the FNWC-PE predicted a significant fraction of the precipitation that occurred in association with the squall line, the NMC-PE produced negligible amounts (figs. 12A, 12B). The implication, therefore, which was corroborated by the other case studies, is that convective activity not in the immediate vicinity of the Low center did not appear to be crucial either to the continuation of development following the onset of cyclogenesis, as illustrated here, or to the actual initiation of development, as will be explicitly discussed with reference to case 7.

Case 6: March 23–24, 1969. Between 0000 and 0600 GMT on March 23, an ill-defined minimum in the pressure field drifted slowly across the Texas Panhandle without developing. The radar observations (fig. 13) indicate that during this interval of time there was some shower activity associated with the Low, but only light precipitation amounts (<0.10 in.) were recorded by hourly rainfall stations.

During the 6-hr period following 0600 GMT, the Low began to deepen (fig. 14), and, as illustrated by the 1200 GMT surface radar composite (fig. 13) and the rainfall histogram of Lake Bridgeport, Tex. (fig. 15), the onset of development was accompanied by an explosive increase in the extent and degree of convection. While the storm continued to intensify between 1500 and 1800 GMT, significant shower activity became dissociated from the Low center.

[6] Isohytal analysis of the actual precipitation amounts is not presented since it is clear from discussion of the observed 1-hr precipitation amounts that the forecast 12-hr amounts are negligible.

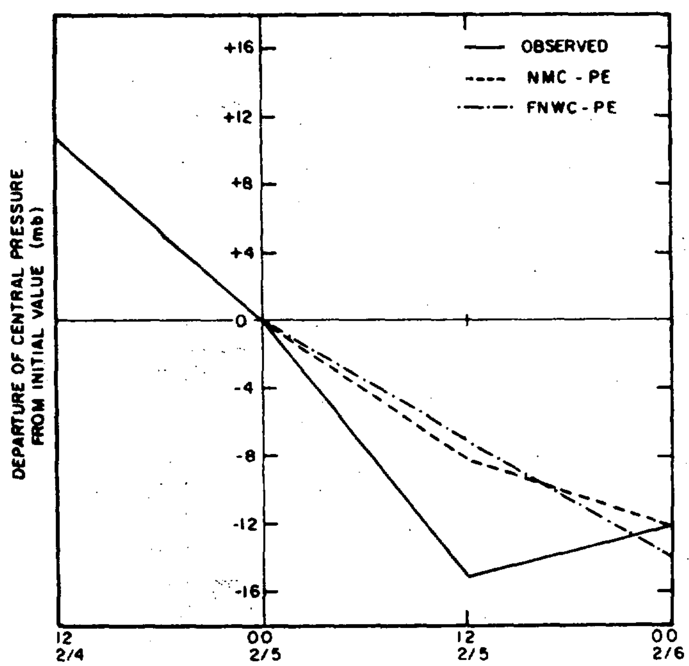


FIGURE 11.—Same as figure 9 for 0000 GMT, Feb. 5, 1971.

One can see from the surface-mean relative humidity charts (figs. 16A, 16B) that the area about the Low at 0000 GMT on March 23 was quite dry. At 1200 GMT, however, shortly after the major outbreak of convective activity, the environment of the storm center was indeed saturated.

Figure 17A indicates that the NMC-PE prognoses from 0000 GMT on March 23 forecast the initiation of development, as was observed, during the first 12 hr following the initial time. The model also predicted during this same interval of time significant amounts of precipitation in association with the forecast center of Low pressure (figs. 18A, 18B). Prognoses generated from 1200 GMT on March 23 (fig. 17B) predicted the continuation of development, without lag, and also forecast substantial amounts of precipitation in association with the forecast Low.

Case 7: February 26–27, 1971. Between 0600 and 1200 GMT on February 26, a weak low-pressure system began to develop (fig. 19) as it moved north-northeastward from

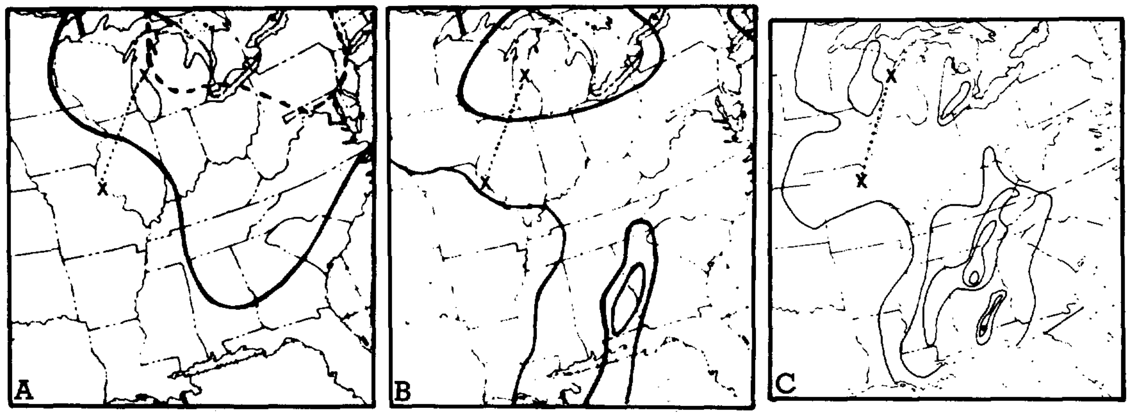


FIGURE 12.—(A) and (B) same as figure 10B (NMC-PE) and 10A (FNWC-PE), respectively, from 0000 GMT, Feb. 5, 1971 data; (C) 12-hr observed precipitation for 0000–1200 GMT, Feb. 5, 1971.

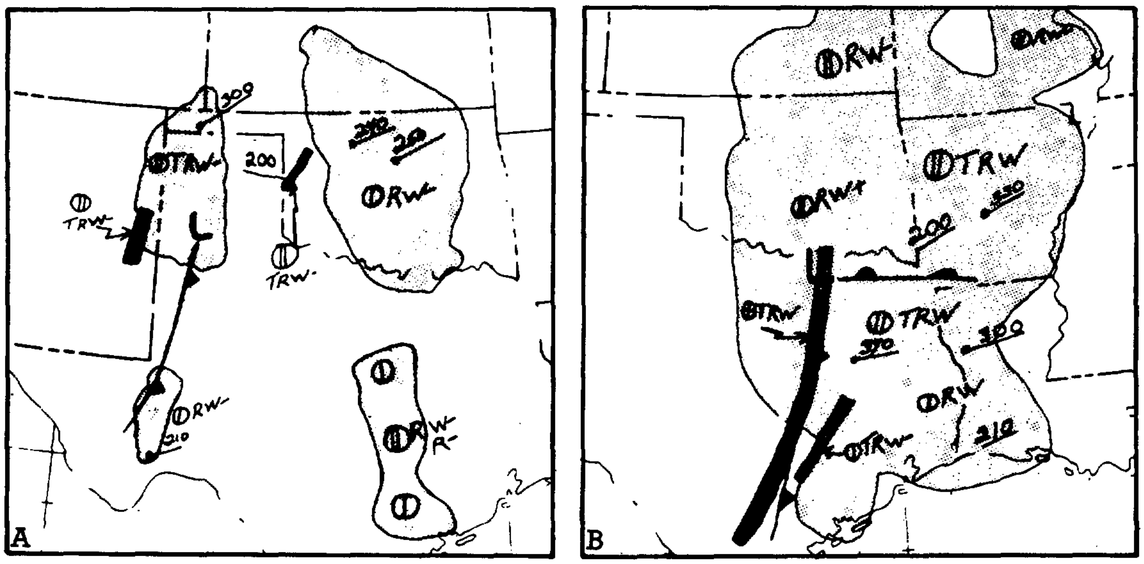


FIGURE 13.—Same as figure 2 for (A) 0000 and (B) 1200 GMT, Mar. 23, 1969.

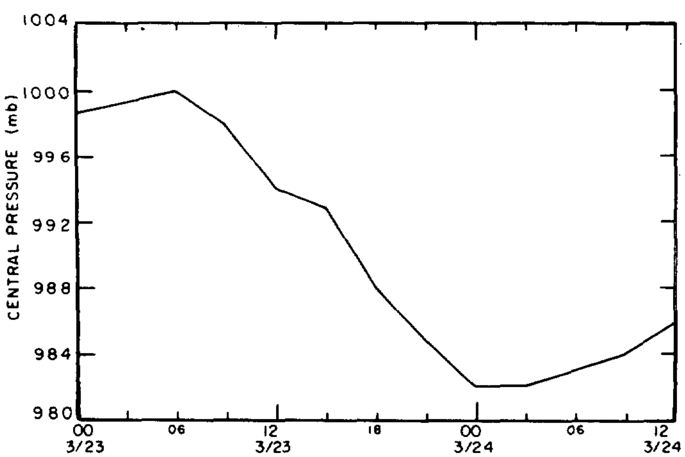


FIGURE 14.—Same as figure 6 for case 6.

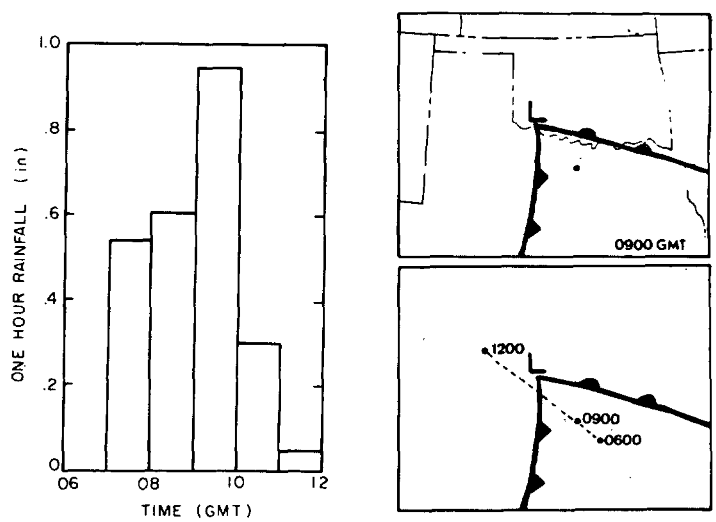


FIGURE 15.—Same as figure 4 for Lake Bridgeport, Tex., for Mar. 23, 1969.

central Nebraska toward eastern Minnesota. The radar charts of 1200 and 1800 GMT on February 26 (fig. 20) show that light showers were associated with the initial development, but, as indicated by the tipping-bucket trace from Minneapolis, Minn. (figs. 21A, 21B), the activity can be considered negligible. The peak intensity of the shower at Minneapolis was just 0.35 in./hr with only 0.08 in. of rainfall recorded in the hour during which the shower occurred (1700–1800 GMT).

In terms of the net 12-hr changes of central pressure, the onset of development did not actually occur until

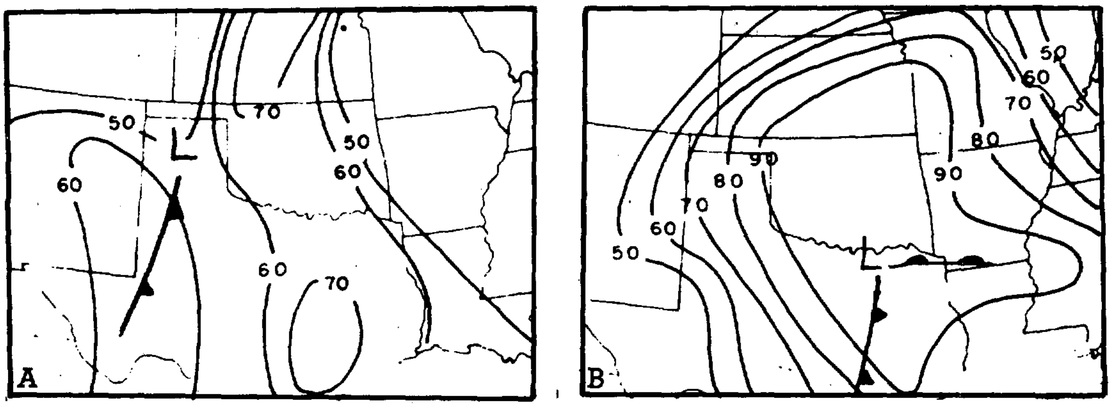


FIGURE 16.—Surface-mean relative humidity charts (percent) for (A) 0000 GMT and (B) 1200 GMT, Mar. 23, 1969

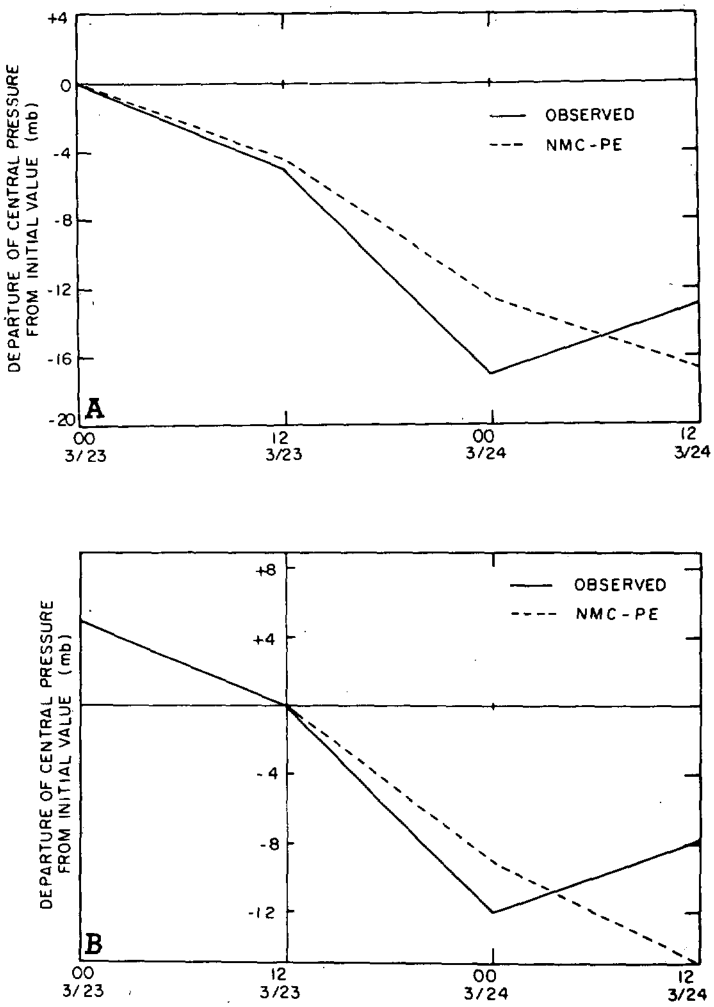


FIGURE 17.—Same as figure 9 for (A) 0000 GMT and (B) 1200 GMT, Mar. 23, 1969.

between 1200 GMT on February 26 and 0000 GMT the next day (fig. 22A). In fact, the Low filled 2 mb during the 12-hr period prior to 1200 GMT on February 26. Figure 22 shows that both the FNWC-PE and NMC-PE prognoses generated from 0000 GMT on February 26 predicted this trend of events. Twenty-four hours after the initial time there was a large error in the absolute difference between the predicted and observed values of central pressure; however, what is significant is that there was no lag in prediction of the initial development. In other words, the time of the onset of cyclogenesis was properly forecast. The same is true for the prognoses from 1200 GMT February 26 data (fig. 22B). Although the magnitude of the predicted initial development was not as great as that observed, the models did forecast the onset of development during the 12-hr period immediately following the initial time.

As an illustration of the apparent unimportance to the initiation of development of convective activity that occurs at the periphery of the storm area, reference is made to the following: the expanded areal coverage of the 1200 GMT February 26 surface radar chart presented in figure 23 illustrates that there was extensive and obviously intense shower activity in the southern United States which was not directly associated with the development of this storm. That is, the convection appeared well before the onset of cyclogenesis and persisted through the later stages of development. Both the NMC-PE and FNWC-PE prognoses generated from 0000 GMT February 26 data did adequately forecast the convective rainfall between 12 and 24 hr after the initial time (i.e., the period during which the onset of development occurred), but the 12-hr forecasts from 1200 GMT February 26 data produced negligible amounts of precipitation during the same period; however, the models in the forecasts generated both from 0000 and 1200 GMT February 26 data properly forecast the onset of development.

Results of cursory examination of 12 additional cases. To augment the nine detailed case studies, a cursory examination was made of 12 additional storms. Each of the 12 cases (as were the nine storms previously analyzed) was an intense cyclogenesis over the eastern two-thirds of the United States or western Atlantic. Data used in the analyses of the convective activity were restricted to the "SM" surface synoptic reports and 6-hr precipitation totals transmitted over teletype. These data alone are not sufficient to describe the detailed distribution and magnitude of convection accompanying a storm's development; however, one can deduce from these data whether or not there was significant shower activity in the vicinity of the Low center during the initital development. Emphasis on storms of the 1971–72 winter season reflected operational implementation of the LFM in October 1971. Only NMC-PE and/or LFM forecasts were available.

The results of the analysis of the 12 storms are presented in table 5. In those cases where the forecasts of both models were available, the conclusions to be drawn

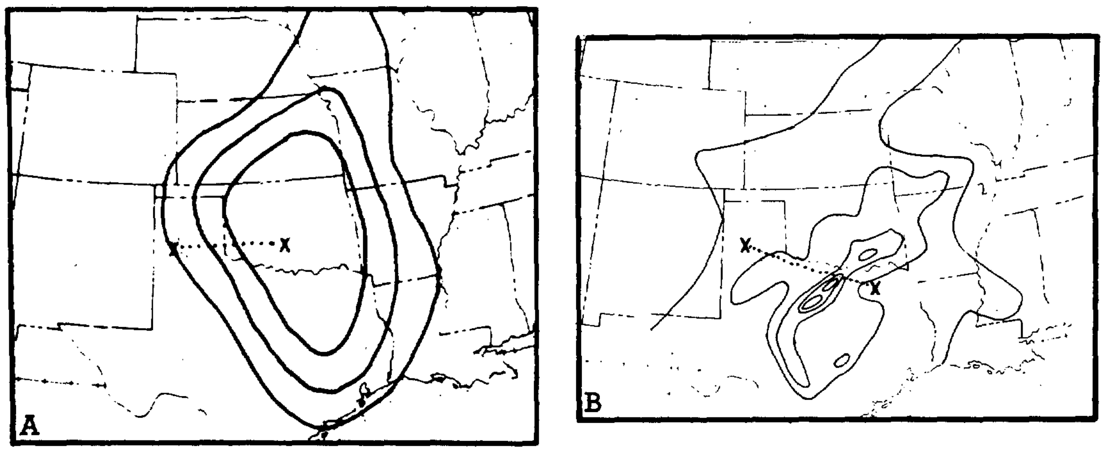


FIGURE 18.—(A) NMC-PE 12-hr precipitation forecast from 0000 GMT, Mar. 23, 1969, and (B) 12-hr observed precipitation for 0000–1200 GMT, Mar. 23, 1969. Contour intervals are as in figure 10. Tracks of respective forecast and observed Low centers are superimposed.

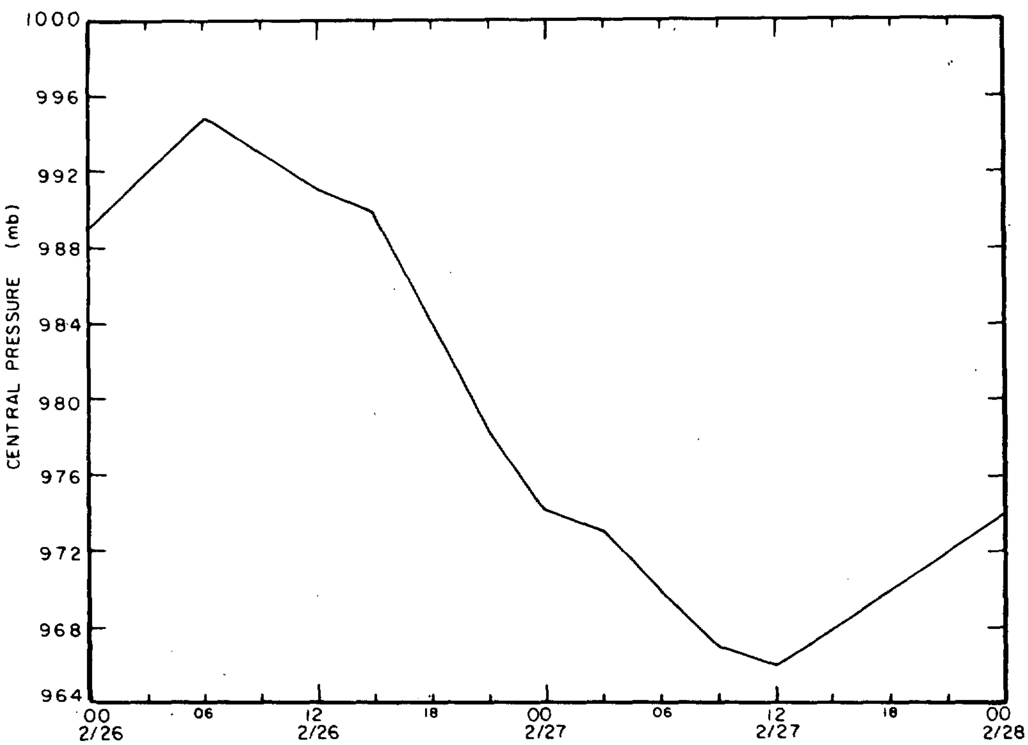


FIGURE 19.—Same as figure 6 for case 7.

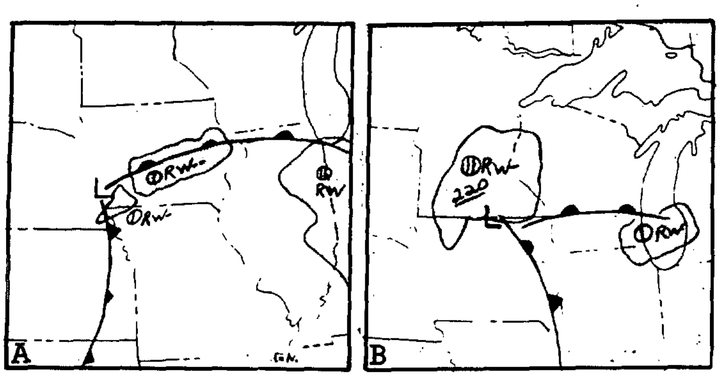


FIGURE 20.—Same as figure 2 for (A) 1200 and (B) 1800 GMT, Feb. 26, 1971.

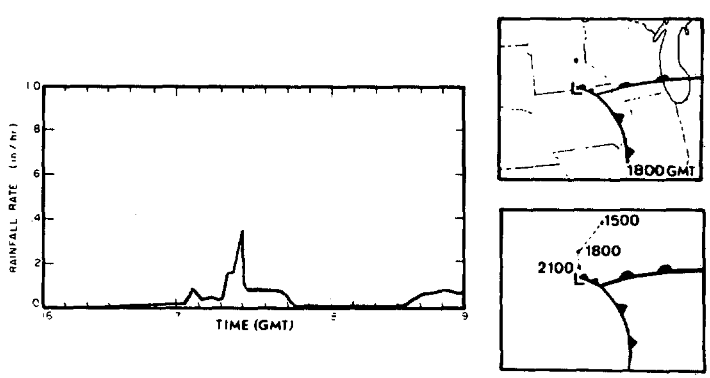


FIGURE 21.—Same as figure 3 for Minneapolis, Minn., on Feb. 26, 1971.

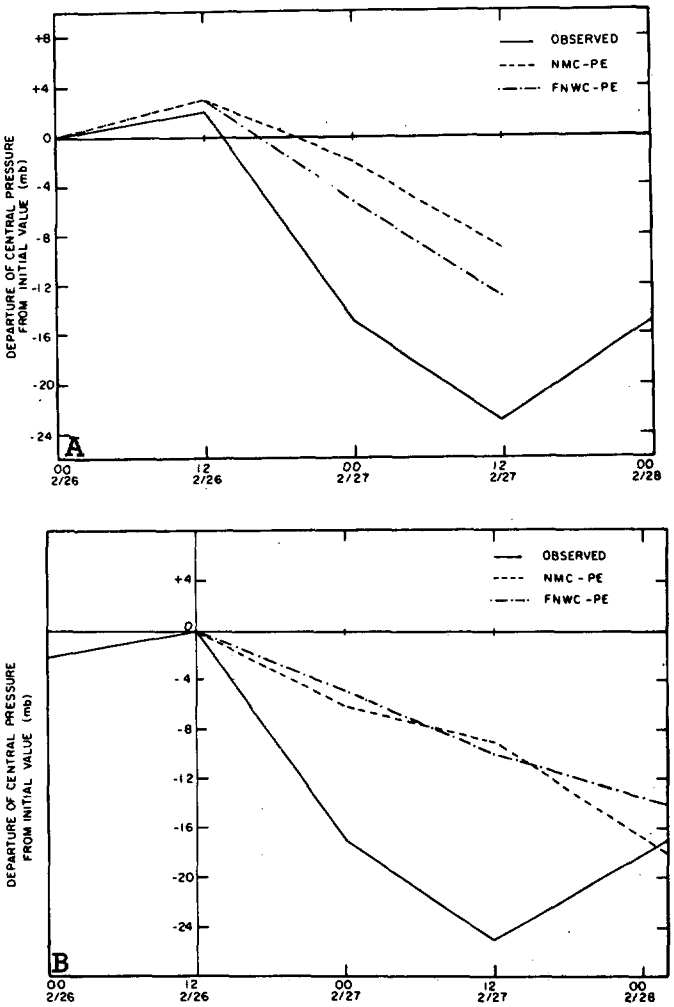


FIGURE 22.—Same as figure 9 for (A) 0000 GMT and (B) 1200 GMT, Feb. 26, 1971.

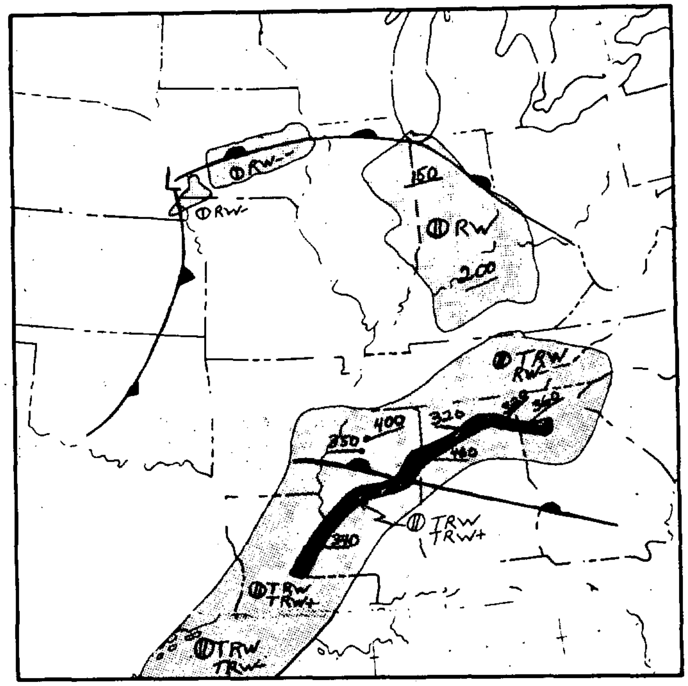


FIGURE 23.—Same as figure 2 for 1200 GMT, Feb. 26, 1971.

TABLE 5.—*Characterization of the initial development of the storms for which a cursory examination was made*

Case	Convective precipitation in storm center?	Environment of Low saturated?	Convective precipitation predicted?	Adequate forecast of the onset of development?
Mar. 6-7, 1971*	Y†	N	N	N
Apr. 5-7, 1971*	Y	N	N	N
Dec. 14-16, 1971	Y	N	N	N
Dec. 9-10, 1971	Y	N	N	N
Feb. 3-4, 1972	Y	N	N	N
Mar. 25-26, 1971*	Y	Y	Y	Y
Feb. 18-19, 1971*	N	N	—	Y
Mar. 23-24, 1971*	N	N	—	Y
Oct. 30-31, 1971	N	N	—	Y
Nov. 1-3, 1971	N	N	—	Y
Nov. 18-19, 1971	N	N	—	Y
Jan. 2-4, 1972	N	N	—	Y

*Those cases for which LFM forecasts were available. NMC-PE forecasts were available in all cases.
†Y=yes, N=No

from each were consistent with one another. Note that the initial development of six storms was accompanied by an outbreak of convective showers in the vicinity of the Low center. In five of these cases, the environment of the Low was unsaturated, the convective precipitation was not adequately simulated, and the initiation of development was not properly forecast. In the one storm in which the convection occurred in a saturated environment, the precipitation and the initiation of development were both predicted. In the six other storms, there was little or no precipitation, either convective or stratiform, in association with the initial development and, in each case, the onset of cyclogenesis was properly forecast.

c. Argument 3: Physical Plausibility and Quantitative Reasonableness

The importance of latent heat release to the development and maintenance of extratropical cyclones has been well established. Danard (1964), for example, has shown that the release of latent heat amplifies the upward motion and thereby increases the low-level convergence. As a result, the sea-level (or 1000-mb) system tends to intensify and move with the center of heaviest precipitation. However, Danard and others who explicitly considered the question (e.g., Bullock and Johnson 1971, Petterssen 1956) expressed the belief that condensational heating does not play a role in the initiation of cyclogenesis, but rather that it affects the subsequent growth. The underlying idea behind this premise is that significant precipitation in association with intense extratropical storms does not occur until after development has commenced and large-scale cloud systems have been formed; that is, after broadscale saturation has been achieved.

Heavy convective rainfall, however, can occur in an unsaturated environment. Moreover, as was documented in the previous subsection, the initial development of some storms does indeed coincide with an outbreak of shower activity prior to large-scale saturation. It is therefore physically plausible that the released latent heat,

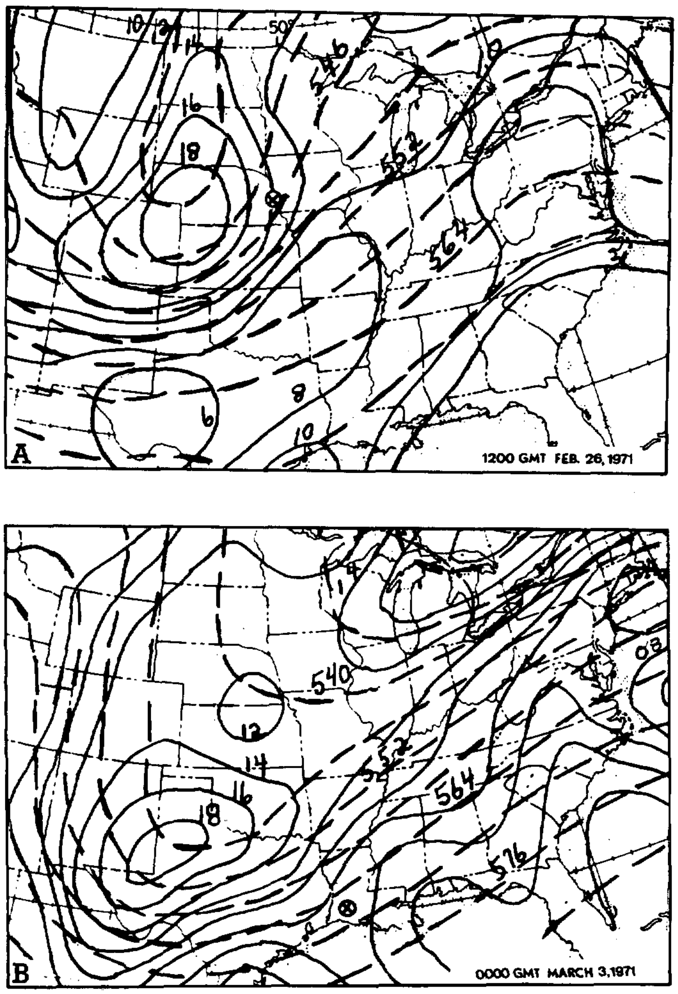


FIGURE 24.—The 500-mb height and vorticity contours at time of initial development of (A) case 7 and (B) case 4. The position of the incipient Low center is indicated by ⊗. Vorticity advection (geostrophic) is inversely proportional to the size of quadrilaterals formed by the height contours and vorticity isopleths. Note that vorticity advection in case 7 is greater, qualitatively speaking, than in case 4. The initial development of case 4 was accompanied by a significant outbreak of convection, while case 7 was not.

through enhancement of the upward motion, plays an important role in the onset of cyclogenesis.

The mechanism generally ascribed to the initiation of cyclogenesis, when the release of latent heat is not taken into account, is the superposition of a region of positive vorticity advection in advance of an upper level trough over a low-level baroclinic (frontal) zone along which the thermal advection is discontinuous (Petterssen 1956). Prior to development, when the vorticity advection is well to the rear of the surface front, the induced vertical motion is opposed by the distribution of horizontal advective cooling. When the region of positive vorticity advection has advanced so that the opposing influence of thermal advection beneath it is weaker or nonexistent, an imbalance is created and development commences.[7]

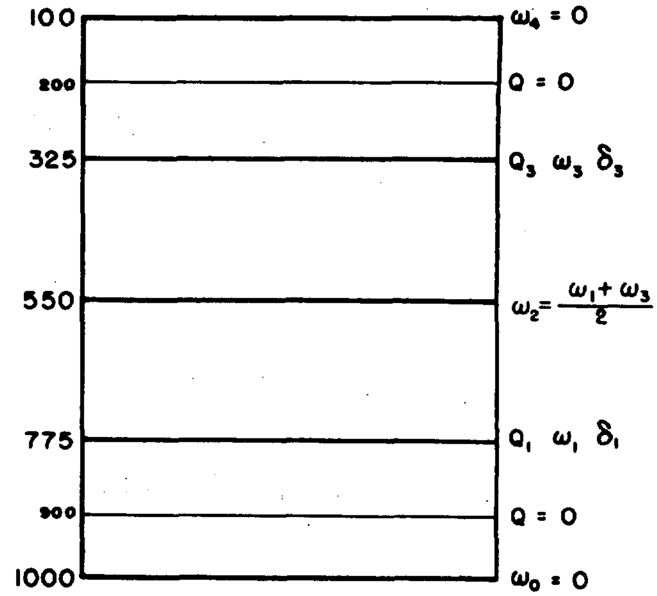


FIGURE 25.—Vertical structure of the model used in the solution of the omega and vorticity equations.

In each of the storms analyzed in this investigation, the development did occur in association with the advance of an upper trough toward a low-level frontal system. As exemplified by figure 24, however, in those storms in which the onset of cyclogenesis was accompanied by convective showers, the vorticity advection over the incipient Low center during the initial stage of development was, qualitatively speaking, less than in other cases. Apparently, an outbreak of convective showers creates the imbalance necessary for development to commence prior to the time when vorticity advection alone would initiate development. From another viewpoint, recall that the error in prediction of the initial development was manifest not in a complete failure to predict the occurrence of cyclogenesis but in a lag in the forecast of the onset of development. Thus, one can infer that the convective release of latent heat initiates cyclogenesis prior to the time when it would have occurred if only the larger scale baroclinic processes were operative. In effect, the release of gravitational instability by small-scale convection triggers the baroclinic instability associated with the large-scale temperature contrast between air masses.

To establish dynamically the magnitude of surface development consistent with the rainfall pattern observed in association with the onset of cyclogenesis, solutions were obtained to the diagnostic quasi-geostrophic omega equation for thermally induced motions (e.g., Danard 1964),

$$\left(\nabla^2+\frac{f_0^2}{\delta}\frac{\partial^2}{\partial p^2}\right)\omega=\frac{R}{c_p p\delta}\nabla^2 Q, \tag{1}$$

and to the vorticity equation,

$$\frac{\partial\zeta}{\partial t}\equiv\frac{1}{f_0}\nabla^2\frac{\partial\varphi}{\partial t}=f_0\frac{\partial\omega}{\partial p}, \tag{2}$$

[7] Surface frictional effects must also be considered. That is, the magnitude of the vorticity advection must be sufficient to offset the opposing influence of friction as well as cold advection.

where φ is the geopotential, $\omega \equiv dp/dt$ represents the vertical motion, ζ is the geostrophic relative vorticity, f_0 is a constant value of the Coriolis parameter, the stability parameter, $\delta \equiv (\partial\varphi/\partial p)(\partial \ln\theta/\partial p)$, is a function only of pressure, and Q is the diabatic heating. Note that the intent here is not to analyze the effect of individual showers but to examine the collective influence of the latent heat released by convective activity in the vicinity of the Low center on the deepening of the cyclone.

The horizontal distribution of rainfall is modeled analytically as an ellipse in which the maximum precipitation rate, P_m, is at the center, and values of P decrease exponentially therefrom. Thus,

$$P(x, y)=P_m e^{-\left(\frac{x^2}{A^2}+\frac{y^2}{B^2}\right)} \tag{3}$$

where A and B are scale factors that specify the minor and major axes (x and y, respectively) of the ellipse defined by $P(x,y)=0.1P_m$.

Precipitation recorded at the ground is assumed to be an adequate reflection of the vertically integrated heating. As has been noted by others (e.g., Charney and Eliassen 1964), however, little is known about the vertical distribution of the latent heat released by cumulus convection. Therefore, detailed treatment of the vertical variation of heating and of other parameters is not justified. Thus, a model with the simplified vertical structure shown in figure 25 was adopted.

The omega equation was applied to levels 1 and 3. With the assumption that the latent heat release is confined to the layer between 900 and 200 mb, the heating at these levels is as follows:

$$Q_1=\frac{2gLP(x,y)\rho}{0.575p_0(1+\nu)}$$

and

$$Q_3=\frac{2\nu gLP(x,y)\rho}{0.575p_0(1+\nu)}. \tag{4}$$

Here, ν is an adjustable parameter that measures the ratio of the upper to lower tropospheric heating (i.e., $\nu=Q_3/Q_1$), L is the latent heat of condensation, and ρ is the density of water.

When vertical derivatives are expressed in finite-difference form, the omega equation at levels 1 and 3 becomes

$$\nabla^2\omega_1+\frac{f_0^2(\omega_3-3\omega_1)}{\delta_1 2(\Delta p)^2}=-\frac{R}{c_p p_1\delta_1}\nabla^2 Q_1$$

and

$$\nabla^2\omega_3+\frac{f_0^2(\omega_1-3\omega_3)}{\delta_3 2(\Delta p)^2}=-\frac{R}{c_p p_3\delta_3}\nabla^2 Q_3. \tag{5}$$

The simultaneous solution of these equations for ω_1 and ω_3 at the center of the precipitation distribution was obtained via a Fourier transform technique outlined in the appendix. A parabolic profile was then fitted to the values of $\omega_0(\omega_0=0)$, ω_1, and ω_2 $[\omega_2=(\omega_1+\omega_3)/2]$ to obtain $\partial\omega/\partial p$ at the 1000-mb surface and thereby enable solution of eq (2) for the 1000-mb geopotential tendency, which may readily be translated to the deepening rate of the sea-level pressure system. The Fourier transform method of solving eq (2) also appears in the appendix.

Table 6.—*Computed deepening rates*

$\nu=Q_3/Q_1$	Surface deepening rate (mb/hr)	$\nu=Q_3/Q_1$	Surface deepening rate (mb/hr)
3.0	−0.61	1.0	−1.15
2.5	−.69	0.67	−1.42
2.0	−.79	.50	−1.52
1.5	−.99		

Observed 1-hr precipitation amounts in the center of storms during the initial phase of development were typically between 0.5 and 1.0 in. (See, e.g., the rainfall histogram of Tulsa in fig. 4.) The value of P_m used in the calculations, therefore, was 0.75 in./hr. On the basis of the characteristic dimensions of the precipitation areas, the values of A and B used in eq (3) were such that the ellipse had major and minor axes of 750 and 250 km, respectively. Average values of δ_1 and δ_2 were ascertained from the values of δ_1 and δ_2 computed for each of the soundings available within a radius of 500 km from the Low center of cases 1–6 during the initial stage of development. Numerically, the mean values of δ_1 and δ_2 were 1.2×10^{-2} and $7.4\times10^{-2}\text{m}^{-2}\cdot\text{s}^{-2}\cdot\text{mb}^{-2}$, respectively.

The computed deepening rates appear in table 6. Values range from −0.61 mb/hr with $\nu=3.0$ to −1.52 mb/hr with $\nu=0.5$. As noted previously, little is known about the vertical distribution of the latent heat released by cumulus convection. Theoretical treatments by various investigators (e.g., Kuo 1965, Kasahara and Asai 1967) predict substantially different vertical variations of the heating. There does appear, however, to be agreement that a larger portion of the heating occurs in the upper rather than the lower troposphere with a ratio of the upper to lower tropospheric heating having a maximum value of about 3. Thus, the most reasonable computed values of the deepening rate are between 0.6 and 1.2 mb/hr. Typical values of the deepening rate observed during the onset of cyclogenesis were about the same.

At this point, a few comments are in order concerning the suitability of the geostrophic equations in this study. The magnitude of the assumed precipitation rate was considerably greater than the 2 cm or less per day consistent with the geostrophic assumption (Phillips 1963). Undoubtedly, if numerical integrations were to be performed with such a large value of the precipitation rate, serious errors in the forecasts would result after a number of time steps. The quantitative reliability of the instantaneous (i.e., diagnostic) relationship between the precipitation rate and computed quantities is not known.

Thus, although the computed deepening rates are comparable with those observed, doubt concerning the quantitative reliability of the geostrophic equations, as well as the relative crudeness of the modeling approximations, must temper any conclusions to be drawn. Nevertheless, the results of the computations are indeed consistent with the notion that the release of latent heat can account for the observed initial development. In other words, it is quantitatively reasonable that cumulus convection through the release of latent heat plays an important role in the initiation of cyclogenesis.

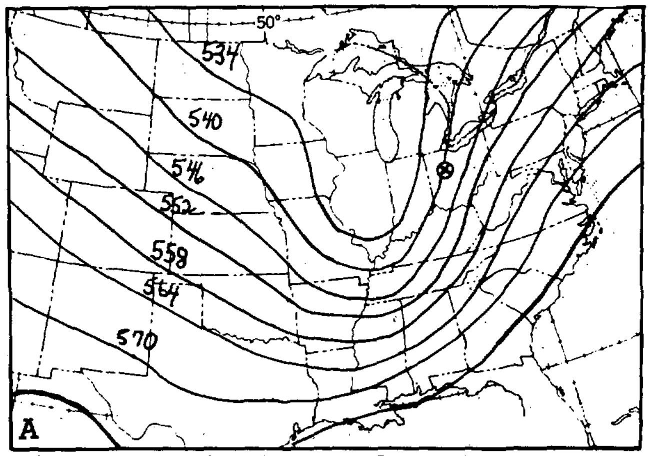
d. Argument 4: Alternative Sources of the Systematic Error

The numerical prognoses in this investigation, with or without proper consideration of cumulus convection, are not perfect representations of the real atmosphere. Errors in the predictions can be introduced by any one or a combination of various physical, dynamical, or computational limitations, such as lack of horizontal and vertical resolution, insufficient initial data, initializing procedures, artificial boundary conditions, and so forth. The possibility must therefore be considered that the failure to forecast properly the onset of development was for reasons other than the failure to predict convective precipitation.

A priori, the most likely alternative explanation is the characteristic tendency for forecast 500-mb troughs to lag behind their observed positions, while the associated surface features move correctly to the east or northeast. Figures 26A and 26B illustrate this type of error. In this 24-hr NMC-PE forecast, the surface Low shows only a small error in position, but the 500-mb trough is slow in its translation eastward. The net effect is that the slope between the 500-mb trough axis and the surface Low is greater than that actually observed.[8] In the forecast, therefore, the surface Low is farther ahead of the region of maximum positive vorticity advection that lies in advance of the upper level trough. Consequently, the failure to properly forecast the onset of development of some storms could conceivably be attributed to failure to predict enough vorticity advection over the incipient Low center.

However, prediction of too great a slope between the 500-mb and surface systems is generally observed to be greatest in the 36-hr forecasts and least pronounced, often nonexistent (especially in the LFM forecasts), in the 12-hr forecasts; and in most cases, the adequacy in predicting the initial development was evaluated on the basis of the 12-hr forecasts. Moreover, the difference between the observed and forecast vorticity advection over the incipient Low centers, assessed qualitatively, was not systematically related to whether or not the onset of development was properly predicted. The greater slope between the forecast 500-mb troughs and surface features likely contributed to the magnitude of the error between the observed and predicted initial development, but it was not crucial to prediction of the initiation of cyclogenesis.

Principal other alternative explanations for the failure to predict the onset of development are (1) inability to resolve all relevant energy-producing systems and (2) initialization procedures. The models can resolve motions only on a scale greater than twice the grid interval; therefore, any processes occurring on a smaller scale, which could be of importance, are eliminated. The smoothing inherent in preparation of initial data for use in primitive-equation models could eliminate from the initial state detail that in the real atmosphere was crucial to the onset of cyclogenesis. Although these, and perhaps other alternative explanations as well, could indeed result in failure to predict the initial development in any given situation, there does not appear to be any reason for the *systematic* error that was observed. That is, no explanation can be given as to why the models consistently failed to predict the initiation of cyclogenesis only when the actual initial development coincided with an outbreak of convective showers and the convective rainfall was not forecast.



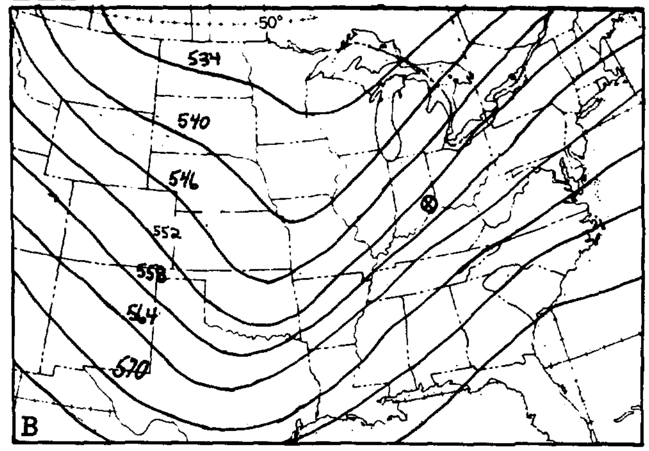


FIGURE 26.—(A) 500-mb analysis for 1200 GMT, Apr. 2, 1970, and (B) NMC-PE 24-hr 500-mb forecast verifying at 1200 GMT, Apr. 2, 1970. Respective positions of observed and forecast surface center of low pressure are indicated by ⊗.

[8] The nature of this type of error, with reference to the NMC-PE, has been discussed by Fawcett (1969). The slowness in translation of the 500-mb trough can reasonably be ascribed to truncation error. The correct motion of the surface system, Fawcett asserts, can be shown experimentally to be due to latent heat feedback. The precipitation predicted in advance of a Low tends to accelerate it toward the center of heaviest rainfall; however, it is the experience of this author that, although latent heat may accentuate the effect, the relative slowness of predicted 500-mb troughs with respect to the surface Lows occurs also when no precipitation is forecast. Furthermore, this type of error was a feature of the NMC-PE *before* precipitation was incorporated into the model (Fawcett 1967). Additionally, it is noted that this error is greater in the FNWC-PE than in the NMC-PE and less in the LFM.

4. CONCLUDING REMARKS

Each of the storms analyzed for this investigation developed over the eastern two-thirds of the United States or western Atlantic. In approximately half the cases, the initial development was accompanied by an outbreak of convective showers in the vicinity of the Low center. On the basis of synoptic experience and the fact that the storms selected for analysis were chosen without prior specific knowledge of the extent of convective activity accompanying their development, the sample is considered representative of the intense cyclones occurring east of the Rocky Mountains. One should recognize, however, that, because of this region's close proximity to a source of warm moist air (the Gulf of Mexico and Caribbean Sea), it is an area particularly susceptible to the generation of the convective instability necessary for the occurrence of shower activity (Fawbush et al., 1951). In geographical areas not so favored, the release of latent heat by cumulus convection is likely an important factor in the initial development of a smaller fraction of storms than in storms east of the Rocky Mountains.

Finally, even in those cases in which the initiation or trend of continued development was forecast, the magnitude of the predicted development was generally less than observed. Whether this reflects lack of incorporation or inadequate formulation of some relevant physical process, computational limitations of the models, or a combination thereof, is not known. Future research should be directed toward answering this question because of its importance both to numerical forecasting and to an improved understanding of the complex phenomenon of cyclogenesis.

APPENDIX

The variables ω_1, ω_3, and P can be expressed in terms of their Fourier transforms, ω_1^*, ω_3^*, and P^*; that is,

$$\omega_1(x,y)=\iint_{-\infty}^{+\infty}\omega_1^*(k,l)e^{i2\pi(kx+ly)}dkdl, \tag{6}$$

$$\omega_3(x,y)=\iint_{-\infty}^{+\infty}\omega_3^*(k,l)e^{i2\pi(kx+ly)}dkdl, \tag{7}$$

and

$$P(x,y)=\iint_{-\infty}^{\infty}P^*(k,l)e^{i2\pi(kx+ly)}dkdl. \tag{8}$$

When these expressions are substituted into eq (5), the following relations are obtained:

$$-(\delta_1M^2+3N)\omega_1^*+N\omega_3^*=\frac{KEM^2P^*}{z_1\nu} \tag{9}$$

and

$$-(\delta_3M^2+3N)\omega_3^*+N\omega_1^*=\frac{KEM^2P^*}{z_3} \tag{10}$$

where

$$z\equiv\frac{p}{p_0},$$

$$M\equiv4\pi^2(k^2+l^2),$$

$$N\equiv\frac{1}{2}\left(\frac{f_0}{p_0\Delta z}\right)^2,$$

$$K\equiv\frac{R}{c_pp_0},$$

and

$$E\equiv\frac{2gL\rho}{0.575p_0(1+\nu)}.$$

Elimination of ω_3^* from eq (9) and (10) yields

$$\omega_1^*=-\frac{P^*KM^2E[z_1\nu N+z_3(\delta_3M^2+3N)]}{z_1z_3\nu[3NM^2(\delta_1+\delta_3)+\delta_3\delta_1M^4+8N^2]}, \tag{11}$$

while elimination of ω_1^* from eq (9) and (10) yields

$$\omega_3^*=-\frac{P^*KM^2E[z_3N+z_1\nu(\delta_1M^2+3N)]}{z_1z_3\nu[3NM^2(\delta_1+\delta_3)+\delta_1\delta_3M^4+8N^2]}. \tag{12}$$

Equations (11) and (12) represent the particular solutions of eq (5). With the boundary conditions $\omega_0=\omega_4=0$, the homogeneous solutions are identically zero.

The Fourier transform of P can be obtained by application of the appropriate theorems of two-dimensional Fourier transforms to the tabulated expression of the Fourier transform of $e^{-\pi(x^2+y^2)}$, (Bracewell 1965).,

The result is

$$P^*=ABe^{-\pi^2(A^2k^2+B^2l^2)} \tag{13}$$

Substitution of eq (13) into (11) and (12), followed by substitution of the results into eq (6) and (7) yields the following for ω_1 and ω_3 (real part):

$$\omega_1=-\frac{4AB\pi^3KE}{z_1z_3\nu}\int_{l=-\infty}^{\infty}\left\{\int_{k=-\infty}^{\infty}\frac{(k^2+l^2)[N(z_1\nu+3z_3)+4\pi^2z_3\delta_3(k^2+l^2)]}{[12\pi^2N(k^2+l^2)(\delta_1+\delta_3)+16\pi^4\delta_3\delta_1(k^2+l^2)+8N^2]}\cos 2\pi(kx+ly)e^{-\pi^2A^2k^2}dk\right\}e^{-\pi^2B^2l^2}dl \tag{14}$$

$$\omega_3=-\frac{4AB^2\pi^3KE}{z_1z_3\nu}\int_{l=-\infty}^{\infty}\left\{\int_{k=-\infty}^{\infty}\frac{(k^2+l^2)[N(z_3+3z_1\nu)+4\pi^2z_1\nu\delta_1(k^2+l^2)]}{[12\pi^2N(k^2+l^2)(\delta_1+\delta_3)+16\pi^4\delta_1\delta_3(k^2+l^2)+8N^2]}\times\cos 2\pi(kx+ly)e^{-\pi^2A^2k^2}dk\right\}e^{-\pi^2B^2l^2}dl. \tag{15}$$

Equations (14) and (15) were evaluated numerically via the 10-point Gaussian Hermite quadrature formulation (International Business Machines 1967).

A value of $\partial\omega/\partial z$ at 1000 mb ($z=1$) was obtained by fitting the parabolic profile,

$$\omega=a(1-z)^2+(1-z)b+c, \tag{16}$$

to ω_0, ω_1, and ω_2. Since $c=0$ ($\omega=0$ at $z=1$),

$$\left(\frac{\partial\omega}{\partial z}\right)_{z=1}=-b; \tag{17}$$

therefore, all that is required is the coefficient b. When eq (16) is applied to levels $z_0=1$, $z_1=0.775$, and $z_2=0.55$, algebraic manipulation yields

$$b=7.7\omega_1-1.1\omega_3. \tag{18}$$

The geopotential tendency, $\partial\varphi/\partial t=\chi$, can be written in terms of its Fourier transform:

$$\chi=\int_{-\infty}^{\infty}\int\chi^*(k,l)e^{i2\pi(kx+ly)}dk\,dl. \tag{19}$$

Substitution of eq (17), (18), and (19) (with ω_1 and ω_3 also written in terms of their Fourier transforms) into the vorticity equation [eq (2)] yields

$$\chi^*=\frac{f_0^2}{M^2p_0}(7.7\omega_1^*-1.1\omega_3^*). \tag{20}$$

When eq (20) is combined with eq (11), (12), and (13), the real part of the solution of eq (19) becomes

$$\chi=-\frac{7.7f_0^2KEAB\pi}{p_0z_1z_3\nu}\int_{l=-\infty}^{\infty}\left\{\int_{k=-\infty}^{\infty}\frac{[N(z_1\nu+3z_3)+4\pi^2(k^2+l^2)]\cos 2\pi(kx+ly)e^{-\pi^2A^2k^2}dk}{12\pi^2N(k^2+l^2)(\delta_1+\delta_3)+16\pi^4\delta_3\delta_1(k^2+l^2)+8N^2}\right\}e^{-\pi^2B^2l^2}dl$$
$$-\frac{1.1f_0^2KEAB\pi}{p_0z_1z_3\nu}\int_{l=-\infty}^{\infty}\left\{\int_{k=-\infty}^{\infty}\frac{[N(z_3+3z_1\nu)+4\pi^2z_1\nu\delta_1(k^2+l^2)]\cos 2\pi(kx+ly)e^{-\pi^2A^2k^2}dk}{12\pi^2N(k^2+l^2)(\delta_1+\delta_3)+16\pi^4\delta_1\delta_3(k^2+l^2)+8N^2}\right\}e^{-\pi^2B^2l^2}dl. \tag{21}$$

Equation (21) was solved using the 10-point Gaussian Hermite quadrature formulation.

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